THE EFFECT OF PREGNANCY ON THE RISK OF INJURY

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Zusammenfassung

Körperliche Aktivität während der Schwangerschaft wirkt sich positiv auf die Gesundheit von Mutter und Kind aus. Trotzdem werden Schwangere häufig gewarnt, sich beim Sport verletzen zu können. Begründet wird dies mit einer Verschlechterung der Stabilität, einer erhöhten Sturzhäufigkeit und Verletzungen des Bindegewebes. Die schlechtere Stabilität und das erhöhte Sturz- und Verletzungsrisiko werden oft mit einer Abnahme der Muskelkraft sowie nachgiebigeren Bändern und Sehnen assoziiert. Während die Bänder des Beckens in der Schwangerschaft nachweislich nachgiebiger werden, gibt es keinen Beleg dafür, dass sich die Sehnen gleichermaßen verändern. Es wird weiterhin vermutet, dass die zunehmende Laxität der Beckenbänder zu Gelenkinstabilität führt und sich negativ auf das Gleichgewicht und das Sturzrisiko auswirkt. Um Verletzungen während der Schwangerschaft vorbeugen zu können, wird in dieser Arbeit erstmalig der Einfluss von Schwangerschaft auf den Muskel-Sehnen-Komplex der unteren Extremitäten untersucht. Weiterhin werden der Effekt auf das statische Gleichgewicht und der Einsatz eines Schwangerschaftsgurtes als potentielle Präventionsmaßnahme gegen Sturzunfälle überprüft.

Zur Untersuchung des Muskel-Sehnen-Komplexes wurde die Morphologie des m. vastus lateralis, die Muskelkraft der Knieextensoren und die Eigenschaften der Patellasehne am Anfang und am Ende der Schwangerschaft sowie ein halbes Jahr nach der Entbindung mittels Ultraschall und Dynamometrie analysiert. Das Gleichgewicht wurde anhand der Grenzen der Stabilität nach anterior und posterior und anhand des Körperschwankens im ruhigen, aufrechten Stand auf einer Kraftmessplatte bei Schwangeren in den unterschiedlichen Schwangerschaftstrimestern und bei Nicht-Schwangeren mit und ohne Schwangerschaftsgurt beurteilt.

Veränderungen im Muskel-Sehnen-Komplex vom Anfang bis Ende der Schwangerschaft deuteten auf ein Muskelwachstum hin, während die Muskelkraft und die Sehnensteifigkeit konstant blieben. Die Sehnenruhelänge nahm während der Schwangerschaft kontinuierlich zu. Der Vergleich zwischen den Trimestern und den Nicht-Schwangeren verdeutlichte, dass Verschlechterungen im statischen Gleichgewicht bereits früh in der Schwangerschaft nachzuweisen sind und nicht mithilfe eines Schwangerschaftsgurtes verringert werden können.

Diese Arbeit liefert relevante Erkenntnisse, die für die Beurteilung des Verletzungsrisikos von Schwangeren und für die Entwicklung geeigneter präventiver Maßnahmen nützlich sind. Es wurde zum wiederholten Male bestätigt, dass Schwangerschaft zu einer Verschlechterung der posturalen Stabilität führt. Ein Schwangerschaftsgurt stellt jedoch keine geeignete Methode zur Verbesserung der Stabilität dar. Während Muskelmorphologie und Sehnensteifigkeit keinen negativen Einfluss zeigen, könnte die zunehmende Sehnenruhelänge zu einer vergrößerten Gelenkbeweglichkeit beitragen und das Risiko für Verletzungen und Stürze erhöhen.

Abstract

Physical activity during pregnancy has beneficial effects on maternal and fetal health. However, pregnant women are frequently cautioned when exercising since impairments in postural stability, an increased incidence of falls and connective tissue injuries have been observed in pregnant women. Both impairments in postural stability and the increased fall and injury risk are believed to result from a loss in muscle strength and an increased compliance of ligaments and tendons. While it is widely accepted that the laxity of the pelvic ligaments increases during pregnancy, there is no evidence that tendons change in the same way. Furthermore, an increased laxity of the pelvic ligaments is believed to lead to joint instability that negatively affects balance ability and increases the risk of falling. This thesis investigates for the first time the effect of pregnancy on the muscle-tendon unit of the lower extremities for the prevention of injuries during pregnancy. Furthermore, this thesis analyzes the effect of pregnancy on static postural stability and examines whether a maternity support belt is an appropriate method for fall prevention in pregnant women.

To investigate the muscle-tendon unit, the morphology of the vastus lateralis muscle, muscle strength of the knee extensors and the properties of the patellar tendon were analyzed in the early and late stage of pregnancy as well as six months after delivery by means of ultrasound and dynamometry. Balance ability was assessed determining the limits of stability in the anterior and posterior directions and the postural sway during upright standing on a force plate in pregnant women in different trimesters of pregnancy and in non-pregnant women with and without maternity support belt.
Changes in the muscle-tendon unit from the early to the late stage of pregnancy indicated muscle growth, while muscle strength and tendon stiffness remained constant. Tendon rest length continuously increased during pregnancy. The comparison between the different trimesters of pregnancy and the non-pregnant women revealed that impairments in static postural stability already occurred early in pregnancy and cannot be reduced using a maternity support belt.

This thesis provides relevant evidence for the assessment of the risk of injury in pregnant women and the development of appropriate prevention strategies. It confirmed that pregnancy is accompanied by impaired postural stability. However, a maternity support belt is not an appropriate method to improve stability. While muscle morphology and tendon stiffness were not negatively affected during pregnancy, the increase in tendon rest length might contribute to an increased joint mobility that may increase the fall and injury risk.

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ACOG	American Colleague of Obstetricans and Gynecologists
A-P	Anterior-posterior
BM	Body mass
BMI	Body mass index
CoM	Center of mass
CoP	Center of pressure
CSA	Cross-sectional area
ECW	Extracellular water
EMG	Electromyography
EP	Early stage of pregnancy
FL	Fascicle length
FM	Fat mass
hRLX	Hormone relaxin
ICW	Intracellular water
LMP	Last menstrual period
LoS	Limits of stability
LP	Late stage of pregnancy
M-L	Medio-lateral
MSB	Maternity support belt

MVC	Maximal voluntary contraction
PP	Postpartum period
SMM	Skeletal muscle mass
T1	First trimester of pregnancy
T2	Second trimester of pregnancy
T3	Third trimester of pregnancy
TBW	Total body water
WHO	World Health Organization
WoP	Week of pregnancy

1 Introduction

Physical activity is well known to be an important component of a healthy lifestyle (DeMaio and Magann, 2009) and is also recommended during pregnancy (Vladutiu et al., 2010; Nascimento et al., 2012; Evenson et al., 2014). In order to be prepared for childbirth and to maintain the cardiovascular capacity, the World Health Organization (WHO) recommends low-intensity aerobic activities such as walking, swimming or stationary cycling, preferably for 30 minutes or more a day (WHO, 2016). In the absence of contraindications, yoga, pilates, and strength training with low weights have also been shown to be safe during pregnancy and are recommended to improve the overall body strength and body posture (ACOG, 2015; O'Connor et al., 2011; de Barros et al., 2010; Zavorsky and Longo, 2011).

Physical activity and exercising during pregnancy significantly reduce the risk of pregnancy associated diseases such as hypertension, preeclampsia (hypertension with proteinuria), and gestational diabetes (DeMaio and Magann, 2009; Nascimento et al., 2012; Zavorsky and Longo, 2011). The prevalence and the severity of other complaints such as back pain (Garshasbi and Faghih Zadeh, 2005; Ritchie, 2003), urinary incontinence (Gameiro et al., 2011; Morkved et al., 2004; Smith et al., 2007), and peripheral edema (Hartmann and Huch, 2005) have also been shown to decrease with regular exercise. Studies on mental health in pregnant women illustrated that engagement in physical activity is further associated with less depression symptoms during and after pregnancy (Robledo-Colonia et al., 2012; Vargas-Terrones et al., 2019) and with increased quality of life (Montoya Arizabaleta et al., 2010).

Maternal exercise also positively affects fetal health as it triggers the growth of villi in the placenta (Jackson et al., 1995) optimizing the blood flow and the transport of nutrients to the fetus (Clapp, 2003; Jackson et al., 1995). It has been shown to reduce the growth of fetal fat mass thus decreasing the birth weight (Clapp, 2003) and the risk of delivery by cesarean section (Owe et al., 2016).

However, despite beneficial effects on maternal and fetal health a high number of pregnant women do not meet the minimum national recommendation of 30 minutes moderate physical activity a day (Mudd et al., 2009) (Figure 1). One Australian study found that 60 % of 18 - 23 year old pregnant women are not sufficiently active (Dobson et al., 2012). The percentage further increases to 70 % of pregnant women aged between 25 - 36 years old (Figure 1). Data from the Canadian Community Health Survey elucidated that non-adherence to the guidelines in pregnant Canadian women is 77 % (Gaston et al., 2012) while in Norway 85 % of pregnant women do not follow the recommendations (Gjestland et al., 2013) (Figure 1). Around 70 % of pregnant women in Denmark (Juhl et al., 2012) and around 58 % of pregnant women in the United States (Zhang and Savitz, 1996) have been found to not participate in any physical activity at all (Figure 1).

In addition to low participation in physical activity, the activity pattern of pregnant women is also characterized by a progressive reduction of the activity level over the different stages of pregnancy (Sternfeld et al., 1995). Sternfeld et al. (1995) interviewed 388 women regarding their activity level from the pre-pregnancy period to the third trimester of pregnancy. The results reveal that the number of women exercising at least three times a week ($\sim$ 20 minutes per session) substantially decreases from 41 % to 14 %. At the same time, the number of sedentary women increases from 50 % in the first trimester of pregnancy to 63 % in the third trimester of pregnancy (Figure 1).

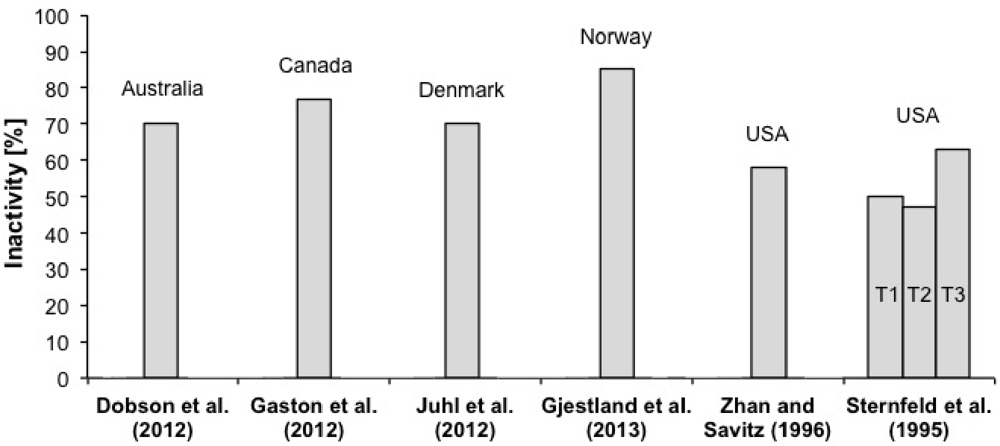


Figure 1: Inactivity during pregnancy. Demonstrated is the percentage of women from Australia, Canada, Denmark, Norway and USA being less active than recommended (Dobson et al., 2012; Gaston et al., 2012; Juhl et al., 2012; Gjestland et al., 2013; Zhang and Savitz, 1996). The bars on the right reflect the percentage of sedentary women from the USA in the first, second and third trimester of pregnancy (T1, T2, T3) (Sternfeld et al., 1995).

The literature demonstrates that there is a broad range of barriers to physical activity during pregnancy (Clarke and Gross, 2004; Cannella et al., 2010; Evenson et al., 2009; Gaston et al., 2012). According to a survey based study on 1,535 pregnant women (Evenson et al., 2009), 85 % of barriers are intrapersonal, of which two-thirds are health related such as musculoskeletal complaints or pregnancy-associated complications. Interpersonal barriers such as a lack of social support and barriers regarding the womens' environment such as a lack of outdoor spaces are relatively uncommon at 2 % and 3 %, respectively. Another barrier discussed in the literature is a lack of information since pregnant women often reported that they were not aware of the benefits and risks of exercise during pregnancy (Clarke and Gross, 2004). Even though obstetricians, gynaecologists and other health care providers are officially instructed to encourage their patients to continue or commence exercising during pregnancy (ACOG, 2015), many pregnant women do not receive any advice regarding physical activity during medical consultation (Evenson et al., 2009).

Around 64 % of pregnant women reported receiving information about risk factors associated with physical activity during pregnancy (Cannella et al., 2010). A study by Cannella et al. (2010) established that around 40 % of this information is from textbooks and pregnancy guidelines, while 26 % of it is from the internet. One of the risks that is frequently described is the increased compliance of connective tissue making pregnant women more prone to injuries when exercising. In a textbook about pathophysiology published by Lee-Ellen C. Copstead and Jacquelyn L. Banasik (2003), it is stated:

> "Tolerance to stress is [...] compromised during pregnancy [...]. During pregnancy, a laxity of tendons and ligaments is noted with a subsequent increased potential for injury." (Danning, 2013, p. 1012)

Another book about skeletal tissue mechanics by Martin et al. (2015) clarifies:

> "Women generally have more compliant tendons and ligaments than men, and this difference can be further increased during pregnancy." (Martin et al., 2015, p. 189)

Nordin and Frankel (2001) reported in their text book about the basics of biomechanics of the musculoskeletal system:

> "A common clinical observation is the increased laxity of the tendons [...] during later stages of pregnancy [...]." (Nordin and Frankel, 2001, p. 115)

While increased hormone levels of relaxin (hRLX) during pregnancy have been found to increase the laxity of the pelvic ligaments in order to facilitate childbirth (Ritchie, 2003; Borg-Stein et al., 2005; Perezgrovas and Anderson, 1982; Musah et al., 1986), there is so far no scientific evidence that the mechanical properties of peripheral ligaments and tendons actually change during pregnancy. Furthermore, in the German Journal of Sports Medicine (Korsten-Reck et al., 2009) studies that never investigated the effect of pregnancy on peripheral ligament or tendon properties are cited as references for the pregnancy-related effect on ligaments and tendons (Artal and O'Toole, 2003; Hartmann and Bung, 1999). Frequently, described effects of pregnancy on tendons are not backed up by references. (Danning, 2013; Martin et al., 2015; Blott, 2010; Klausmann, 2002; Engels et al., 2009).

Supplying incorrect and unsubstantiated information leads to misconceptions about physical activity during pregnancy and, thus, to inadequate recommendations. It has, for example, become a frequent practice to make pregnant women aware of an increased risk of extensive overstretching (Blott, 2010; Klausmann, 2002; Engels et al., 2009) making pregnant women more vulnerable to muscle and connective tissue injuries when exercising (Kainer and Nolden, 2015; Klausmann, 2002). This is why the Federal Centre for Health Education in Germany (BZgA, 2018) officially recommends that pregnant women avoid stretching exercises. As the risk of extensive torsions, sprains and traumata (Lutter and Lee, 1993; Kiechle, 2011; Engels et al., 2009; Eberlein, 2008; Drewes, 2011) may further increase during weight-bearing activities, the American College of Obstetricians and Gynecologists (ACOG) suggests pregnant women "Avoid jerky, bouncy, or high-impact motions [...]" (ACOG, 2019, p. 2).
The literature also suggests that pregnant women may be more susceptible to lose their balance. While ligamentous laxity is assumed to impair the stabilization of the joints (ACOG, 2019), it is claimed that tendinous laxity diminishes motor control (Pearson et al., 2011) and postural reaction time (McCrory et al., 2010a) as muscle fascicle shortening is assumed to be slower during force production in a muscle-tendon unit with a more compliant tendon. Both effects are believed to manifest as an increased risk of falling in pregnant women (ACOG, 2019; Onambele et al., 2006; Pearson et al., 2011; McCrory et al., 2010a).

However, concerns regarding injuries and falling due to more compliant ligaments and tendons negatively affect the attitude towards physical activity and exercise among pregnant women. The numbers pertaining to the participation of pregnant women in physical activity (Mudd et al., 2009; Dobson et al., 2012; Gaston et al., 2012; Gjestland et al., 2013; Juhl et al., 2012; Zhang and Savitz, 1996; Sternfeld et al., 1995) illustrate that it is extremely important to encourage women to continue exercising during pregnancy. Increased physical activity during pregnancy may help to reduce the prevalence of pregnancy associated diseases and to foster healthy development of the fetus.

To be able to develop substantiated and appropriate recommendations regarding safe exercise it is important to understand the morphological, functional and psychological changes during pregnancy that may negatively affect the risk of injury in pregnant women. The most important changes are highlighted in the following chapter.

2 Morphological, functional and psychological changes during pregnancy

Pregnancy is a unique time period in which a women experiences numerous physical changes. The present chapter provides an overview of scientific observations regarding morphological and functional alterations in pregnant women.
As pregnancy is further accompanied by changes in the mental state, a short review about anxiety symptoms and the implication on maternal and fetal health is provided at the end of this chapter.

2.1 Morphological changes

In this subsection, the relevant aspects of pregnancy-related changes in body mass and body composition are reviewed. Following this, current knowledge on the effect of pregnancy on muscles, bones, and the connective tissue is described.

2.1.1 Body mass

Weight gain during pregnancy is essential for an uncomplicated pregnancy and the healthy growth of the fetus (Hytten and Paintin, 1963; Eastman and Jackson, 1968; Soltani et al., 2017; Scholl et al., 1995; Prentice et al., 1989; Brown and Avery, 2012; Billewicz and Thomson, 1957; IOM, 2009). The gained weight differs individually and is highly dependent on the pre-pregnancy body mass index (BMI). In pregnant women with a normal pre-pregnancy BMI, the increase from the early (EP) to the late stage of pregnancy (LP) is on average 12.5 kg (Billewicz and Thomson, 1957). However, as an inadequate amount of weight gain during pregnancy can negatively affect the birth outcome, underweight women are recommended to gain more weight during pregnancy, up to 18 kg, whereas overweight and obese women are advised to gain less weight with 5 - 11.5 kg (IOM, 2009).

The rate of weight gain during pregnancy increases exponentially from the EP to the middle stage of pregnancy. Thereafter, the rate of weight gain can be considered as a linear increase (Figure 2). In the first trimester (T1), which is the 1^{st} - 13^{th} week of pregnancy (WoP), the embryo develops into a fetus. Body mass (BM) marginally increases with

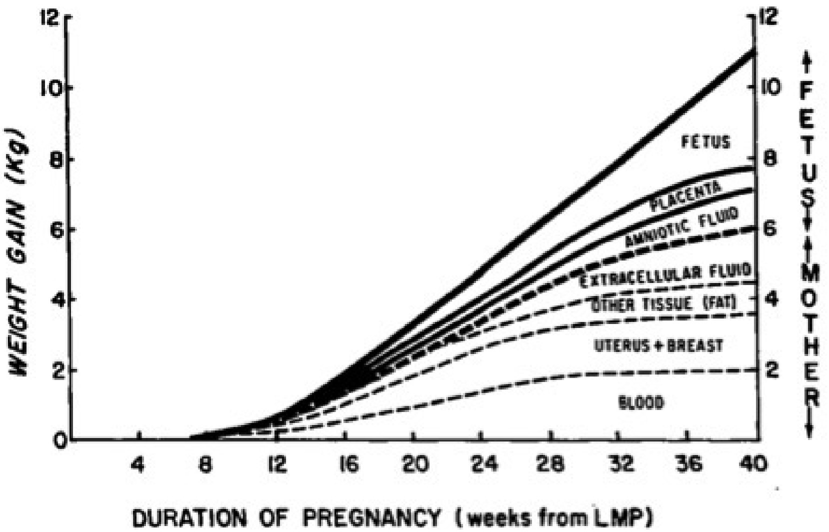


Figure 2: Maternal and fetal components of weight gain during pregnancy (LMP: last menstrual period) (Pitkin, 1976, p. 491).

1 - 2 kg in total (Pitkin, 1976). From the middle stage of pregnancy the rate of weight gain increases more rapidly with 0.4 kg a week (Figure 2) (Rasmussen et al., 2010). In the second trimester of pregnancy (T2), which is the 14^{th} - 26^{th} WoP, the increase is primarily related to alterations in maternal compartments such as the enlargement of the uterus, breast tissue, blood volume as well as fat accumulation and water retention (Pitkin, 1976). The growth of the fetus and other fetal related changes such as an increase in the placenta and the amniotic fluid are more substantial in the third trimester of pregnancy (T3) between the 27^{th} - 40^{th} WoP (Pitkin, 1976).

In healthy and non-obese women, most of the gained weight during pregnancy decreases in the postpartum period (PP) (Pitkin, 1976). Six weeks postpartum, BM is still on average 3 kg greater compared to the values measured for the 13^{th} WoP (Soltani et al., 2017); however, 24 weeks postpartum the values have returned to the pre-pregnancy level (Soltani et al., 2017).

Women who fail to lose pregnancy weight within six months postpartum have been observed to be on average 6 kg heavier ten years after delivery compared to women who were able to lose the gained weight (Rooney and Schauberger, 2002).

In conclusion, pregnant women tend to gain more weight in the LP than in the first weeks of pregnancy. Weight gain not only occurs due to the growing fetus but also due to maternal changes such as fat accumulation and water retention in the tissue in order to guarantee the healthy development of the fetus. The amount of weight gain differs between individuals varying from 5 - 18 kg. In normal circumstances, BM returns to pre-pregnancy values 24 weeks postpartum.

2.1.2 Body composition

Weight gain during pregnancy is partly attributed to increased water retention in the tissue and partly to increased fat accumulation. The following chapters briefly discuss the available evidence on pregnancy-related changes in both parameters.

2.1.2.1 Body water

Around 50 - 70 % of the total weight gain during pregnancy is attributed to water retention in the intracellular and the extracellular spaces (Hytten and Thomson, 1968; Valensise et al., 2000; Lukaski et al., 1994). Extracellular water (ECW) is interstitial fluid between the tissue cells and the plasma volume. It accounts for around 43 % of the total body water (TBW) (Lof and Forsum, 2004). Intracellular water (ICW) is inside the tissues' cells and is likely to reflect maternal changes such as the growth of the breast tissue or the uterus (Larciprete et al., 2003). ICW accounts for 56 % of the TBW (Lof and Forsum, 2004).

Water retention during pregnancy is necessary for maternal health and the healthy development of the child during and after pregnancy. Insufficient retention in the ECW can reduce the plasma volume expansion, which has been shown to negatively affect the mother's cardiac output and the children's birth weight (Mardones-Santander et al., 1991; Ghezzi et al., 2001). In contrast, a large increase in the ECW is associated with the formation of edema in the ankles, legs, and feet (Thomson et al., 1967; Ponnapula and Boberg, 2010). This is commonly associated with gestational hypertension and preeclampsia (hypertension with proteinuria) (Thomson et al., 1967).

Bioelectrical impedance analyses demonstrated that the largest increase in the TBW occurs between T2 and T3 (Larciprete et al., 2003; Lof and Forsum, 2004; Valensise et al., 2000; Van Loan et al., 1995). During this period, the increase in ICW and ECW is

11 - 21 % (∼2 - 5 l) (Larciprete et al., 2003; Lof and Forsum, 2004; Valensise et al., 2000). After delivery the amount of accumulated fluid is likely to return slowly to the initial levels. Two weeks postpartum, the ECW and ICW are typically reduced by 6 % and 4 % (Lof and Forsum, 2004) and after four weeks by 22 % (Van Loan et al., 1995). After 60 days, the TBW and ECW return to pre-pregnancy values (Ghezzi et al., 2001).

In sum, around the half of the total weight gain during pregnancy is attributed to water retention in the intracellular and the extracellular spaces. An insufficiently high or low water retention negatively affects maternal and fetal health. TBW significantly increases in the advanced stages of pregnancy and typically returns to pre-pregnancy values within 60 days postpartum.

2.1.2.2 Body fat

The increase in BM is further related to fat accumulation (Soltani et al., 2017; Cho et al., 2011; Sidebottom et al., 2001) which is necessary to meet the energy demands of the mother and her child (Villar et al., 1992). While an insufficient increase in fat mass (FM) negatively affects the birth weight, an excessive increase is associated with gestational diabetes (Balani et al., 2014).

A study by Lederman et al. (1999) demonstrated that the FM increase between the 14^{th} and 37^{th} WoP is on average 6 kg for underweight women, 3.8 kg for women with a normal weight, and 3.5 kg for overweight women. However, these data solely reflect the FM increase in pregnant women with an adequate weight gain as recommended by the Institute of Medicine (IOM, 2009). Women with a larger increase in weight gain are likely to expect a larger amount of FM increase of up to 6.9 kg (Lederman et al., 1999).

According to Sidebottom et al. (2001) conducting skinfold thickness tests at the thigh in 557 women, the amount of accumulated subcutaneous fat significantly decreases by 9 % within the first six weeks postpartum. Butte et al. (1997) using different body composition models (two-, three- and four-component models based on TBW, underwater weighing, skinfold thicknesses test, total body potassium, dual-energy X-ray absorptiometry and total body electrical conductivity) in 35 women observed a 10 % decrease in FM between the third to the twelfth month postpartum. No study demonstrating that the amount of accumulated fat during pregnancy entirely returns to pre-pregnancy levels was found. However, since Smith et al. (1994) detected a waist-to-hip ratio that was four times larger in women twelve months postpartum compared to non-pregnant women, it is believed that some of the fat accumulated during pregnancy remains after delivery. This is in compliance with findings from Cho et al. (2011) who conducted bioelectrical impedance analyses in 41 women. The authors reported an increase of 25 % in visceral fat that took place from the second day after delivery to the sixth month (Cho et al., 2011). As visceral fat increases the risk of cardiovascular diseases and diabetes mellitus (Onat et al., 2004), pregnancy is speculated to be associated with future diseases (Cho et al., 2011).

Summing up, fat accumulation during pregnancy is necessary to guarantee healthy growth of the fetus. It contributes about 30 - 50 % to the total weight gain during pregnancy. The FM decreases in the PP; however, there is evidence that some of the accumulated fat remains after delivery.

2.1.3 Musculoskeletal system

Pregnancy has also been found to affect the properties of the musculoskeletal system as there is usually a considerable change in BM and body shape. The information available on pregnancy-related changes in muscle, bone, ligament and tendon properties is reviewed in the following subchapters.

2.1.3.1 Muscles

Due to an increased risk of urinary incontinence in pregnant women, research on changes in the muscle properties during pregnancy primarily focuses on the pelvic floor muscles and the abdominal muscles (Morkved et al., 2004; Gameiro et al., 2011; Smith et al., 2007). The high prevalence of incontinence at 35 % (Wijma et al., 2001) is believed to be associated with increased hRLX levels as well as musculoskeletal changes during pregnancy (Wijma et al., 2001; Harvey, 2003; Miodrag et al., 1988). Elongated muscle fibers are assumed to diminish the supporting function of the pelvic organs (Wijma et al., 2001; Harvey, 2003; Miodrag et al., 1988) which may cause an uncontrolled opening of the urethra.

Urinary incontinence is further associated with reduced strength in the pelvic floor muscles (Gameiro et al., 2011). Gameiro et al. (2011) subjectively evaluated muscle strength in 50 pregnant and 50 non-pregnant women by performing transvaginal digital palpations. For 58 % of pregnant women in the 36^{th} WoP, the degree of contraction strength was significantly reduced compared to the degree of strength that was determined in non-pregnant women. In contrast, when muscle strength was assessed objectively using a portable perineometer, the strength values did not differ between the groups (Gameiro et al., 2011).

In order to treat pregnancy-related pelvic floor dysfunctions, strength training of pelvic floor muscles is recommended (Morkved et al., 2004). Abdominal muscle training has also been found to positively affect the properties of the pelvic floor muscles as these muscles contract synergistically (Ferla et al., 2016; Arab and Chehrehrazi, 2011). However, for pregnant women exercises involving the abdominal muscles should be chosen with care (Gilleard and Brown, 1996) since the abdominal muscles undergo major structural changes due to the progressive growth of the uterus (Gilleard and Brown, 1996). With the stretched abdominal wall, the four muscle pairs of the rectus abdominis muscle covering the anterior region of the abdomen become separated. The distance between the muscle pairs can increase by up to 62 mm (Gilleard and Brown, 1996). Since this structural alteration is accompanied by a changed orientation and a changed line of action of the muscles, this may negatively affect force production (Gilleard and Brown, 1996). Therefore, pregnant women from the 26^{th} WoP commonly demonstrate a reduced ability to perform a curl-up and to stabilize the pelvis against resistance (Gilleard and Brown, 1996). Eight weeks postpartum when the abdominal muscles have almost regain their initial position, trunk flexion performance improves again (Gilleard and Brown, 1996).

Pregnancy is also assumed to negatively affect the endurance of back muscles. However, reduced muscle endurance has been found solely in pregnant women with pelvic girdle pain (Gutke et al., 2008). When these women were instructed to hold an isometric back extension position for as long as possible, the endurance was significantly shorter with 35 s as compared to values from pregnant women without pain with 53 s (Gutke et al., 2008).

Information about pregnancy-related changes in peripheral skeletal muscle strength is scarce. Two studies investigating muscle strength in pregnant women have been published (Treuth et al., 2005; Atay and Basalan Iz, 2015). Atay and Basalan Iz (2015) reported a 9 % reduced handgrip strength in the LP compared to the middle stage of pregnancy. The second study by Treuth et al. (2005) analyzed the lower and upper body strength in the pre-pregnancy phase and six weeks after delivery. The data illustrate a loss in muscle strength in both the upper and the lower body; however, the largest loss with 24 % occurred in the lower body.

There are also little data on pregnancy-related changes in peripheral muscle morphology. An animal study investigated architectural properties of the tibialis anterior muscles of the hind limbs in rats at the middle (10 - 12 days) and late stage (19 - 21 days) of gestation as well as four weeks and twelve weeks postpartum (Alperin et al., 2015). None of the assessed parameters fiber length, sarcomeres length, physiological cross-sectional area (CSA) and muscle mass changed during and after gestation.
In contrast, alterations were detected for the fiber content of the abdominal muscles demonstrating a larger number of slow fibers in gestating rats as compared to virgin rats (Vesentini et al., 2018). As slow fibers are 30 % stiffer than fast fibers (Malamud et al., 1996), a potential pregnancy-related fast-to-slow fiber type shift may be accompanied by an increased stiffness of the muscle tissue (Bisch et al., 2006).

While pregnancy is associated with muscle weakness, there is evidence to suggest that hormonal changes during pregnancy are likely to trigger muscle growth of smooth muscles such as the uterus (Rundgren, 1974). Hormonal changes during pregnancy have also been found to improve the regeneration capabilities of peripheral skeletal muscles and to overcome negative effects of aging (Falick Michaeli et al., 2015). Falick Michaeli et al. (2015) compared the regeneration process of myotubes in the injured hind limb muscles of gestating and non-gestating mice at different ages by immunostaining the relevant cells. The regeneration of the muscle in the non-gestating older mice (ten months non-pregnant) did not significantly differ from that of the young non-gestating young mice (twelve weeks non-pregnant) (Figure 3). However, in both the young (twelve weeks pregnant) and older gestating mice (ten months pregnant), the muscle regeneration was significantly improved compared to the non-gestating mice (Falick Michaeli et al., 2015)(Figure 3).

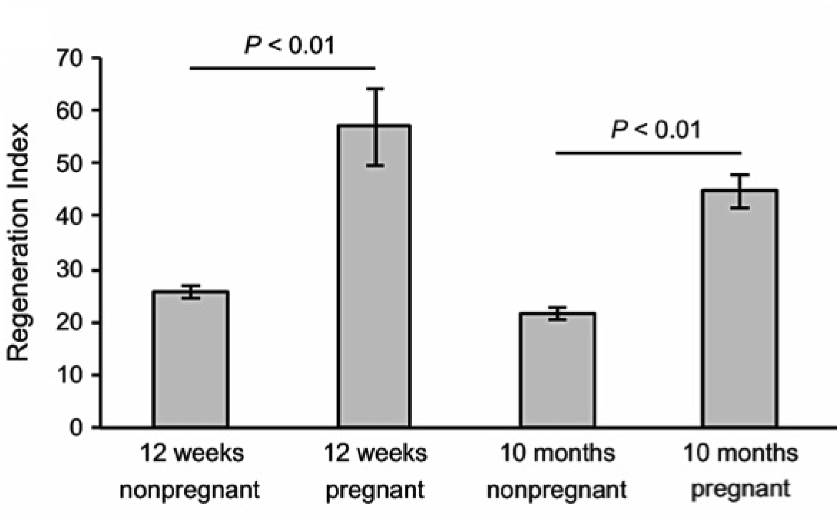


Figure 3: Regeneration capabilites of injured hind limb muscles in non-gestating and gestating mice at different ages. The regeneration index quantifies results of the immunostaining experiment (adapted from Falick Michaeli et al., 2015, p. 699).

Finally, pregnancy is assumed to positively affect the immunomodulatory properties of muscles. The risk of bout onset of multiple sclerosis has been found to be significantly reduced during pregnancy (Runmarker and Andersen, 1995). Further, in patients who gave birth to a child, the risk of the onset of the disease and the relapse rate has been reported to be significantly reduced compared to women without children (Runmarker and Andersen, 1995; Airas and Kaaja, 2012).

In conclusion, pregnancy is associated with changes in the muscle properties that negatively affect endurance and force production, in at least the back extensors, the pelvic floor muscles and the abdominal muscles (Wijma et al., 2001; Harvey, 2003; Miodrag et al., 1988; Morkved et al., 2004; Gameiro et al., 2011; Smith et al., 2007; Gilleard and Brown, 1996; Noren et al., 2002; Gutke et al., 2008). While the number of studies investigating changes in the peripheral muscles during pregnancy is low, one study detected a loss in the upper body strength (Atay and Basalan Iz, 2015). Another study reported a loss in strength for the lower body. However, as strength values were determined in the PP, the results are more likely to reflect changes during the recovery phase than actual changes during pregnancy (Treuth et al., 2005). Thus, there is so far no study that actually establishes a loss in the lower body muscle strength during pregnancy.
There is evidence to suggest that pregnancy provides conditions that may be favorable

for retaining muscle strength. Hormonal changes during pregnancy have been shown to trigger muscle growth (Rundgren, 1974) and to improve the regeneration capabilities of skeletal muscles (Falick Michaeli et al., 2015). In women with multiple sclerosis, pregnancy has further been found to affect the immunomodulatory properties of the muscles reducing the relapse rate of the disease (Runmarker and Andersen, 1995; Airas and Kaaja, 2012).

2.1.3.2 Bones

Increased mechanical loading due to an increased BM is known to positively affect bone mineralization (Vandewalle et al., 2013). However, during pregnancy increased demand for calcium by the growing fetus is likely to negate load bearing related adaptations in the bones. The largest calcium transfer from the mother to her child occurs during T3, when the fetal skeleton absorbs 80 % ($\sim$24 g) of its total calcium requirements (Kovacs, 2001; Christiansen et al., 1976; Kalkwarf et al., 1997). In this period, the maternal hip, the femoral neck, the radial shaft, the spine, the pelvis, and the heels have been shown to demonstrate significantly reduced bone density values with a loss of 2 - 4 % (Tojo et al., 1998; Drinkwater and Chesnut, 1991; Yamaga et al., 1996; Bjorklund et al., 1999; Kolthoff et al., 1998; Black et al., 2000; Shefras and Farquharson, 1996; Naylor et al., 2000; Drinkwater and Chesnut, 1991).
In the PP, the daily loss of calcium by lactation is approximately similarly high as the maternal calcium loss in the LP (Kovacs, 2001). Nevertheless, bone density loss in the PP has been reported to be twice as great (Tojo et al., 1998; Drinkwater and Chesnut, 1991; Christiansen et al., 1976; Atkinson and West, 1970; Lamke et al., 1977; Hayslip et al., 1989; Matsumoto et al., 1995; Kalkwarf and Specker, 2002; Laskey et al., 1998).

Changes in bone density during and after pregnancy are believed to be triggered by changes in the endocrine system. Increased hRLX levels during pregnancy are deemed to activate osteoclasts in order to resorb the bone substance. This facilitates the passing on of a larger amount of the maternal calcium to the fetus (Akesson et al., 2004). However, the larger extent of bone loss in the PP is associated with reduced hormone levels of estrogen as has been previously shown in women during menopause (Brown, 2008). Estrogen is a central element for bone growth (Cromer, 2008) and is responsible for osteoblastic activity at all ages (Brown, 2008).

According to Kalkwarf and Specker (2002), the skeleton is likely to regain the pre-pregnancy bone mass within 18 - 24 months postpartum. The duration of the recovery phase, however, is highly dependent on the duration of lactation and the onset of the first menses after childbirth (Kalkwarf and Specker, 2002). Women who have their menses during the first five months after delivery have been found to regain their initial bone density level by six months postpartum (Polatti et al., 1999).

It can be summarized that the maternal skeleton loses around 2 - 4 % of its bone density during pregnancy (Tojo et al., 1998; Drinkwater and Chesnut, 1991; Yamaga et al., 1996; Bjorklund et al., 1999; Kolthoff et al., 1998; Black et al., 2000; Shefras and Farquharson, 1996; Naylor et al., 2000; Drinkwater and Chesnut, 1991). This change is associated with an increased demand for calcium by the growing fetus especially in the LP (Kovacs, 2001; Christiansen et al., 1976; Kalkwarf et al., 1997). The loss in bone density further increases in the PP (Tojo et al., 1998; Drinkwater and Chesnut, 1991; Christiansen et al., 1976; Atkinson and West, 1970; Lamke et al., 1977; Hayslip et al., 1989; Matsumoto et al., 1995; Kalkwarf and Specker, 2002; Laskey et al., 1998). However, the underlying mechanism behind this effect needs to be further investigated. It is likely that reduced levels of estrogen in this period inhibit bone growth (Brown, 2008). Bone density returns slowly to pre-pregnancy values. The duration of the recovery phase can vary between six months and two years after delivery (Polatti et al., 1999; Kalkwarf and Specker, 2002).

2.1.3.3 Ligaments and joints

It is widely accepted that pregnancy increases the compliance of the ligaments in the pelvic area (Ritchie, 2003; Borg-Stein et al., 2005; Rundgren, 1974; Perezgrovas and Anderson, 1982; Musah et al., 1986). Increased compliance is attributed to increased hRLX levels being secreted by the corpus luteum in the ovary and by the placenta (Conrad and Baker, 2013; Goh et al., 2013). The hormone hRLX has been found to trigger the synthesis of new collagen by activating fibroblasts in the collagen fibers (MacLennan, 1991). This contributes to a change in the collagen fiber distribution from large to small diameters (Blecher and Richmond, 1998) decreasing the stiffness of the tissue (Rundgren, 1974; Vollestad et al., 2012).

Increased compliance of the pelvic ligaments is essential to facilitate the passage of the fetus during childbirth (Rundgren, 1974; Ritchie, 2003; Borg-Stein et al., 2005; Perezgrovas and Anderson, 1982; Musah et al., 1986). Previous radiological analyses in pregnant women have shown that the widening of the symphysis can increase by up to 9 mm (reviewed in Young, 1940). Increased compliance of the pelvic ligaments during pregnancy is at the same time assumed to increase pelvic joint mobility which is associated with the high prevalence of low back pain and pelvic girdle pain in pregnant women (Ritchie, 2003; Kristiansson et al., 1996; MacLennan et al., 1986b; Mens et al., 2009).

Apart from the pelvic ligaments, other types of ligaments are also assumed to be affected by increased compliance during pregnancy. One study by Rateitschak (1967), for example, detected a significant increase in tooth mobility in six of seven women in their last month of pregnancy. As the authors did not establish any changes in the bone socket, they concluded that the increased mobility is most likely attributed to an increased compliance of the periodontal ligaments (Rateitschak, 1967).

Evidence from hypermobility measurements with gonio- and hyperextensometers (Schauberger et al., 1996; Lindgren and Kristiansson, 2014; Östgaard et al., 1993; Marnach et al., 2003) that demonstrates an increased range of motion in several peripheral joints during pregnancy may indicate that peripheral ligaments become more compliant during pregnancy, as well. Schauberger et al. (1996) conducted joint mobility measurements at the knee joint using a clinical KT1000 arthrometer. The authors observed an 83 % larger extent of anterior tibial translation relative to the femur in the ninth month of pregnancy compared to in the EP. Other research groups (Lindgren and Kristiansson, 2014; Östgaard et al., 1993) investigated the abduction angle of the fourth finger and found the largest increase with 2 - 5 % in the 24^{th} WoP. An increase in the flexion-extension and mediolateral (M-L) mobility of the wrist has been observed to be 10 % and 5 % larger in T3 compared to the values measured in T1 (Marnach et al., 2003).

There is disagreement about whether the pregnancy-induced peripheral joint laxity remains after delivery. Dumas and Reid (1997) used a clinical KT1000 arthrometer in 65 pregnant women to establish a 14 % decrease of anterior tibial translation from the fifth month of pregnancy until the fourth month postpartum. In contrast, Schauberger et al. (1996) using the same KT1000 arthrometer in 21 pregnant women reported a further increase in the anterior tibial translation of 34 % two weeks after delivery (Schauberger et al., 1996). An increase in joint laxity in the PP has also been observed by Lindgren and Kristiansson (2014) who detected the largest abduction angle of the left fourth finger at as late as 13 weeks postpartum.

A pregnancy-related increase in peripheral joint laxity is believed to be direction-specific. Measures from pregnancy and the PP demonstrated that the tibia displacement relative to the femur in the anterior direction significantly increases, while the displacement in the coronal plane and in the posterior direction decreases (Chu et al., 2019).
Furthermore, peripheral joint laxity seems to be related to the parity status. While Chu et al. (2019) observed an increased anterior knee joint laxity in primiparous women only, previous studies, in contrast, reported an increased extent of finger joint mobility in multiparous women (Calguneri et al., 1982; Östgaard et al., 1993). According to Calguneri et al. (1982), the largest extension of the metacarpophalangeal joint of the index finger occurs during the second pregnancy. This change is likely to be persistent as the authors observed similar values in the third and fourth pregnancy (Calguneri et al., 1982).

In addition to range of motion measures in humans that do not directly measure joint laxity, Hart et al. (2000) determined the knee joint laxity in gestating and non-gestating rabbits by means of in vitro testing, thereby assessing translational movements of the tibia relative to the femur. Similar to observations in pregnant women, the knee joints of gestating rabbits demonstrated a significant increase in laxity compared to the non-gestating rabbits.

While an increased laxity of the pelvic joints during pregnancy is assumed to be associated with increased hRLX levels, it is also likely that hRLX leads to an increased peripheral joint laxity. However, two experimental studies failed to establish a relationship between these parameters (Schauberger et al., 1996; Marnach et al., 2003). Schauberger et al. (1996) detected the highest hRLX levels in the EP when the extent of anterior tibial translation relative to the femur was marginally increased by 2 % of the total increase in the end of pregnancy. Marnach et al. (2003) also reported the largest hRLX levels in T1 when the flexion-extension angle of the wrist was at the minimum. Only one study on pregnant women was found to report a positive correlation between hRLX levels and the ability to actively raise a straight leg from a lying position. This finding might indicate that hRLX is more likely to affect the pelvic ligaments than the peripheral ligaments (Vollestad et al., 2012).

An increased knee joint laxity has also been assumed to be attributed to increased levels of estrogen during pregnancy. Charlton et al. (2001) determined the anterior knee joint laxity in the knees of 20 pregnant women using KT1000 arthrometer in the 30^{th} WoP and the fifth to the seventh week postpartum. In line with the 215-fold increase in the estrogen levels during pregnancy (during pregnancy: 10,755 ng/l, postpartum: 50 ng/l) the authors also measured significant larger knee joint laxity values during pregnancy (increase: 33 %) than in the PP.

There is no evidence supporting the assumption that a reduced stiffness of peripheral ligaments may lead to an increased peripheral joint laxity as has been shown for the pelvic joint laxity (Young, 1940; Ritchie, 2003; Kristiansson et al., 1996; MacLennan et al., 1986b; Mens et al., 2009). Two animal studies analyzed gestation-related changes in the mechanical properties of ligaments at the knee joint by means of material testing (Hart et al., 2000; Rundgren, 1974). Hart et al. (2000) did not observe any effect of gestation on the ligament stiffness of the medial collateral ligaments of gestating rabbits. Similarly, Rundgren (1974) did not observe any changes in the mechanical properties of the posterior cruciate ligament in gestating rats (Rundgren, 1974). It was only within the first three days of the PP that the maximum load was reduced; it returned to control levels or levels higher than the control level thereafter.

In sum, pregnancy leads to an increased compliance of the pelvic ligaments to facilitate childbirth (Rundgren, 1974; Ritchie, 2003; Borg-Stein et al., 2005; Perezgrovas and Anderson, 1982; Musah et al., 1986). It is assumed that the compliance of other ligaments such as the peripheral ligaments may similarly increase (Schauberger et al., 1996; Lindgren and Kristiansson, 2014; Östgaard et al., 1993; Marnach et al., 2003). Increased

compliance of peripheral ligaments is believed to be associated with an increased peripheral joint laxity that has been found to remain after delivery and to further increase with repeated pregnancies (Calguneri et al., 1982; Östgaard et al., 1993).
In contrast to the pelvic joint laxity, peripheral joint laxity is unlikely to be attributed to increased hRLX levels during pregnancy (Schauberger et al., 1996; Marnach et al., 2003). Instead, increased levels of estrogen may affect the peripheral joints (Charlton et al., 2001). Information from two studies reveals that peripheral ligament stiffness does not change during pregnancy (Hart et al., 2000; Rundgren, 1974).

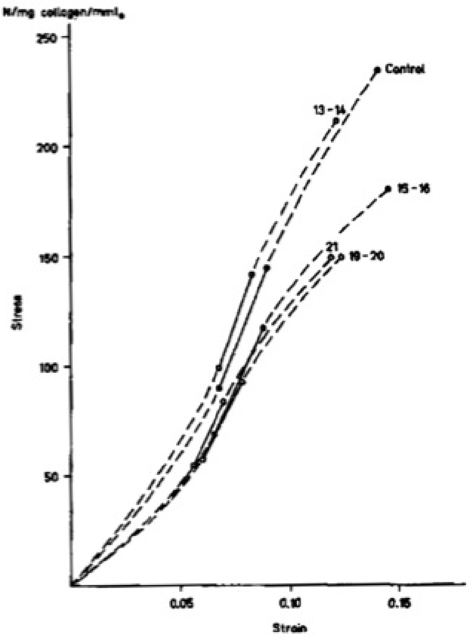
2.1.3.4 Tendons

While pregnancy is assumed to affect the properties of the peripheral ligaments, in several textbooks, journal articles, and pregnancy guidelines (Danning, 2013; Nordin and Frankel, 2001; Martin et al., 2015; Blott, 2010; Klausmann, 2002; Engels et al., 2009; Korsten-Reck et al., 2009) it is stated that hormonal changes during pregnancy similarly affect the tendon tissue. However, scientific evidence of this effect is insufficient as only one animal study (Rundgren, 1974) actually investigated pregnancy-associated alterations in the composition and the mechanical properties of tendons.

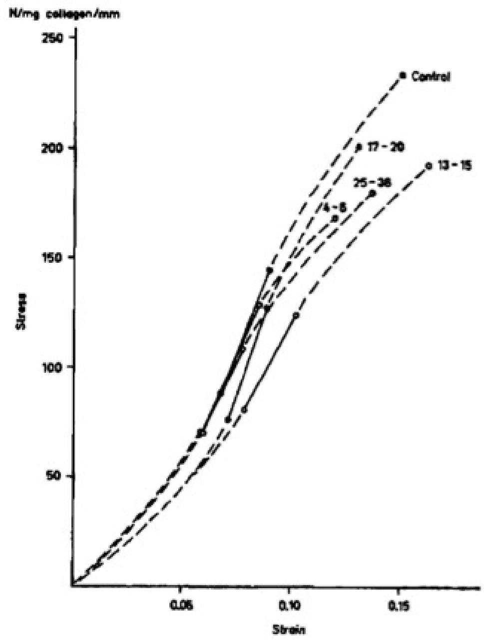
Rundgren (1974) investigated changes in the collagenous framework of the musculus digiti quinti tendon in young rats at different phases of gestation as well as in non-gestating rats. The author observed a significantly reduced amount of collagen per unit specimen length in the early stage of gestation (6^{th} - 10^{th} day). During the late stage of gestation (19^{th} - 20^{th} day) the amount of collagen was found to be significantly greater compared to the non-gestating rats. Early in the PP (4^{th} - 6^{th} day after delivery), the amount of collagen was not different to that of the non-gestating rats. However, as values significantly increased in the 13^{th} - 15^{th}, 17^{th} - 20^{th} and 25^{th} - 38^{th} days, pregnancy-related changes in the tendon are likely to remain during the recovery phase (Rundgren, 1974).

Assessing the mechanical properties of the same tendon by material testing, Rundgren (1974) observed similarly high-strain values in the gestating and non-gestating group (Figure 4A). However, stress values and the maximum load were temporarily increased during 6^{th} - 10^{th} days of gestation (not presented in Figure 4A), but decreased again during the 19^{th} - 21^{st} days of gestation. The stress values in later days of gestation were not significantly different from the controls. It was only at the start of the linear region that the values from the 19^{th} - 21^{st} day group and from the 21^{th} day group were significantly reduced compared to the non-gestating rats. The modulus of elasticity was not affected by gestation.

The postpartum stress values were similar for the groups except for the 4^{th} - 6^{th} day (Figure 4B). During this period, gestating rats demonstrated reduced stress values at the start of the linear region of the stress-strain curve. No differences between the groups have been found for the modulus of elasticity.



A)



B)

Figure 4: A) Stress-strain relationships of the musculus digiti quinti tendon of primiparous and non-gestating rats (Control). Values at the top of the curves denote days of gestation (Rundgren, 1974, p. 86). B) Stress-strain relationships of the musculus digiti quinti tendon of rats during the postpartum period and non-gestating rats (Control). Values at the top of the curves denote days of the postpartum period (Rundgren, 1974, p. 87).

Rundgren (1974) also analyzed the wet weight of collagen fibers per unit length in rat tail tendons. Differently to the amount of collagen in the musculus digiti quinti tendon that increased during the late stage of gestation (19^{th} - 20^{th} day), the wet weight per unit length in the tail tendons did not change during gestation. The author concludes that the pattern of reactivity seems to be different in the two types of tendons. This may point towards a tendon-specific effect of pregnancy.

Hypothesizing that tendon properties may be affected by the status of parity, Rundgren (1974) further analyzed the mechanical tendon properties in multiparous rats. An effect of parity on the musculus digiti quinti tendon on the modulus of elasticity was not established (Figure 5). However, the author established a significantly larger maximum strain of 17 % in multiparous rats as compared to virgin rats (Rundgren, 1974).

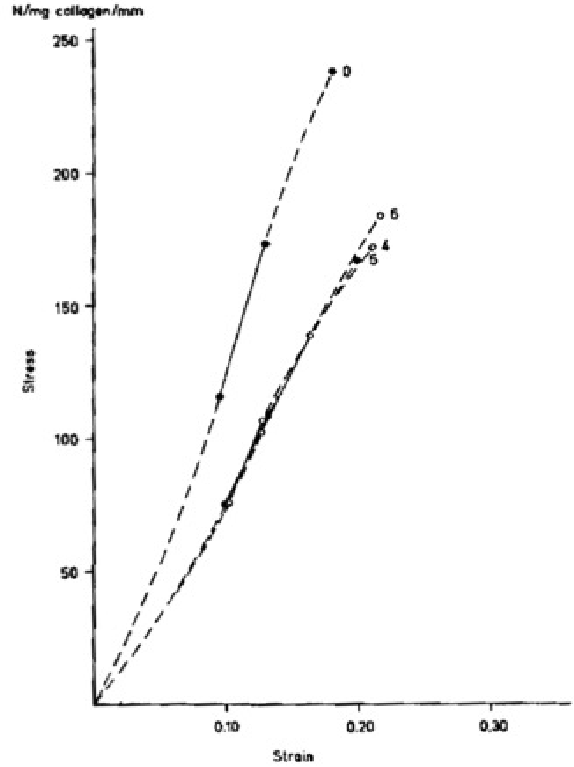


Figure 5: Stress-strain relationships of the musculus digiti quinti tendon of multiparous rats. Values at the top of the curves denote the number of pregnancies (Rundgren, 1974, p. 88).

While the effect of hormonal changes during pregnancy on tendon properties in humans is unknown, several in vivo measures in non-pregnant women were performed in order to analyze the hormonal effect of oral contraceptives and different menstrual phases on tendon adaptation (Pearson et al., 2011; Bryant et al., 2008; Hansen et al., 2013). These in vivo measures involved simultaneous recordings of ultrasound-based data of tendon elongation and dynamometric data during isometric contractions to facilitate a non-invasive assessment of the tendon mechanical properties.

The in vivo measures of the Achilles tendon demonstrated that the use of oral contraceptives with synthetic estrogen and progestogen leads to increased tendon stiffness (Bryant et al., 2008). In contrast, Hansen et al. (2013) did not observe differences in patellar tendon stiffness in either oral contraceptive users or non-users or between the different phases of the menstrual cycle.

It seems likely that hormonal effects are tendon-specific, since Pearson et al. (2011) also observed different adaptation pattern for the patellar and gastrocnemius tendon. The authors did not detect any relationships between fluctuating hRLX levels during the menstrual cycle and gastrocnemius tendon stiffness. However, the stiffness of the patellar tendon significantly decreased with elevated hRLX levels. While elevated hRLX levels are likely to decrease the patellar tendon stiffness in non-pregnant women, this effect may be potentiated in pregnant women as hRLX levels have been found to be ten times greater during pregnancy (Pearson et al., 2011). Studies are needed to investigate this effect, preferably by performing equivalent in vivo studies such as those already performed in non-pregnant women.

Summing up, gestation increases the amount of collagen in the musculus digiti quinti tendon of rats in the late stage of gestation (Rundgren, 1974). This change is assumed to be tendon-specific and is likely to remain after delivery (Rundgren, 1974). Despite temporary changes in the stress values and the maximum load at the early stage of gestation, gestation does not affect the mechanical properties of the tendon, much less the modulus of elasticity (Rundgren, 1974). However, repeated pregnancies in rats are likely to increase the maximum strain of the tendon tissue (Rundgren, 1974).

In humans, the effect of pregnancy on tendon mechanical properties is unclear. However, as it is known from studies on menstruating women that increased hRLX levels are associated with reduced patellar tendon stiffness (Pearson et al., 2011), considerably larger hRLX levels during pregnancy may lead to an even more pronounced reduction in tendon stiffness.

2.2 Functional changes

Morphological changes during pregnancy such as an increased BM and changed body shape have been shown to affect the functional properties of the musculoskeletal system. In the following paragraphs the most important effects of pregnancy on body posture, locomotion, and balance ability are summarized.

2.2.1 Posture

A significant amount of the weight gained during pregnancy is attributed to changes in the abdominal mass. The increased abdominal mass in combination with the simultaneous impairment in the functional properties of the abdominal muscles (Gilleard and Brown, 1996; Smith et al., 2007) and the increased compliance of the sacroiliac ligament (Ritchie, 2003) is assumed to reduce the ability to stabilize the pelvis (Gilleard and Brown, 1996; Ritchie, 2003). This change is associated with an increased anterior tilt of the pelvis in pregnant women with an increase of 4° between T2 and T3 (Franklin and Conner-Kerr, 1998).

A) B) C)

Figure 6: Changes in body posture during pregnancy. Figure A illustrates a typical lumbar lordosis of a non-pregnant woman. Figure B demonstrates a pregnant woman with an anterior shift of the center of mass and a lack of compensatory adaptation of the lumbar spines. Figure C demonstrates a typical pregnant woman with an increased lumbar lordosis shifting the center of mass in the posterior direction (Whitcome et al., 2007, p. 1075).

The increased abdominal mass and the changed orientation of the pelvis are likely to shift the center of mass (CoM) in the anterior direction (Figure 6A → B) (Whitcome et al., 2007). However, in order to prevent forward movement and to maintain an upright standing position, it is assumed that pregnant women unconsciously (Whitcome et al., 2007) respond with an altered body posture shifting the CoM back in the posterior direction (Opala-Berdzik et al., 2010; Fries and Hellebrandt, 1943; Krkeljas, 2018). One compensatory mechanism that is commonly observed is increased lumbar lordosis (Figure 6C) (Whitcome et al., 2007; Krkeljas, 2018; Östgaard et al., 1993; Dumas and Reid, 1997; Franklin and Conner-Kerr, 1998; Ireland and Ott, 2000) as it is frequently associated with the high incidence of low back pain and pelvic gridle pain in pregnant women (Franklin and Conner-Kerr, 1998; Ritchie, 2003; Kristiansson et al., 1996; MacLennan et al., 1986b; Mens et al., 2009). Other potential strategies to move the CoM in the posterior direction may be increased thoracic kyphosis (Betsch et al., 2015), hyperextended knee joints, an increased hyperextension of the cervical spine, a raised head, and a changed head position, i.e. shifted 29 mm in the posterior direction (Franklin and Conner-Kerr, 1998).

Investigations into the location of the center of pressure (CoP) in 33 pregnant women during motionless standing on a force plate demonstrated that the CoP in the LP is shifted approximately 4 mm in the posterior direction compared to in the EP (Opala-Berdzik et al., 2010). This "overcompensation" (Fries and Hellebrandt, 1943, p. 379) was previously observed by Fries and Hellebrandt (1943) who determined longitudinal changes in the average location of the CoM within the base of support based on photographs of one woman standing. Already during puerperium when the head, back and knees have been found to regain their initial position, the CoM returns to the EP location (Fries and Hellebrandt, 1943). This position is maintained for six months postpartum indicating that pregnancy-related changes in body posture are not accompanied by long-term effects (Opala-Berdzik et al., 2010).

Fries and Hellebrandt (1943) further investigated changes in the location of the CoM in the coronal plane. However, alterations were marginal and differed from less than half of changes measured in the sagittal plane. The small effect of pregnancy on the coronal plane may be related to an increased stance width that increases with the different stages of pregnancy from 17.9 cm to 21.9 cm (Jang et al., 2008). According to Jang et al. (2008), the increased stance width is an important mechanism to increase the base of support and to enhance stability in the M-L direction (Jang et al., 2008; Dumas and Reid, 1997). In contrast, Nagai et al. (2009) suggest that pregnant women use a larger stance width to unconsciously improve the lower body's sensitivity to somatosensory information. As demonstrated by a previous study by Day et al. (1993), the increased stance width results in a locked position of the knee joints facilitating a uniform movement of the legs and the pelvis. This may enhance proprioceptive sensitivity to motions in the lateral direction

(Day et al., 1993).

In conclusion, pregnancy-related changes in the abdominal mass, the sacroliliac ligaments, and the abdominal muscles are accompanied by an anterior tilt of the pelvis and an anterior shift of the CoM (Whitcome et al., 2007). In order to compensate for these changes and to guarantee upright standing, pregnant women respond with a changed body posture shifting the CoM 4 mm in the posterior direction (Opala-Berdzik et al., 2010; Fries and Hellebrandt, 1943; Krkeljas, 2018). The changed location of the CoM in the sagittal plane is temporary and returns to the initial position after delivery (Opala-Berdzik et al., 2010). Changes in the coronal plane during pregnancy are marginal as the somatosensory input, proprioception, and stability are likely to be enhanced due to an increased stance width during pregnancy.

2.2.2 Locomotion

The gait pattern during pregnancy has been observed to be significantly different from the gait pattern in non-pregnant women (Bertuit et al., 2015). According to Bertuit et al. (2015), pregnant women show a 21 % reduced preferred walking speed and tend to a 13 % smaller step length and a 25 % increased step width compared to non-pregnant women. Pregnant women have also been found to shorten the swing phase by 7 % and the single support phase by 5 %, while increasing the stance phase by 3 % and the double support phase by 41 % (Bertuit et al., 2015; Ribeiro et al., 2011; Forczek and Staszkiewicz, 2012; Mei et al., 2018; Branco et al., 2014).
The largest changes in the gait pattern primarily occur in the LP (Carpes et al., 2008; Bird et al., 1999; Hagan and Wonh, 2010). Alterations commonly return to pre-pregnancy values within four to six months after delivery (Bertuit et al., 2015; Hagan and Wonh, 2010; Forczek and Staszkiewicz, 2012). However, there is also evidence that some characteristics such a slower gait speed and a reduced swing phase can last as long as eight months postpartum (Bertuit et al., 2015).

The mechanisms underlying diverse alterations in the gait pattern during pregnancy are controversially discussed in the literature. According to Gimunova (2015), decreases in gait velocity are assumed to reflect the protection of the fetus against extensive concussions and shaking. Other authors (Bird et al., 1999; Bertuit et al., 2015; Branco et al., 2014; Forczek and Staszkiewicz, 2012; Lymbery and Gilleard, 2005; Blaszczyk et al., 2016) suggest a compensatory mechanism in order to reduce energy costs. However, as already shown in other scenarios, an increased step width and a too low gait velocity seem to be inefficient from an economical point of view (Donelan et al., 2001; McNeill Alexander, 2002). Therefore, the strategy to stabilize the heavier body is likely to be the prime concern (Branco et al., 2014).

An increased need to stabilize the body in the LP may be shown by increased ground reaction forces in the medial direction during the stance phase of the gait cycle (Lymbery and Gilleard, 2005; Mei et al., 2018; Ribeiro et al., 2011). Due to the increased step width, it seems favorable to perform the push-off from the medial side of the great toe towards the contralateral leg (Lymbery and Gilleard, 2005). Non-pregnant women with a narrow step width use all toes for the push-off (Lymbery and Gilleard, 2005).
Some pregnant women have been found to generate increased pressure loads in the lateral part of the foot (Elsayed et al., 2017). However, shifting the heavier body in the lateral direction results in abnormal stresses of the fifth metatarsal bone. This is associated with the high prevalence of foot pain in 31 % of pregnant women (Elsayed et al., 2017).

Reduced ground reaction forces during stair climbing may also indicate an adaptive mechanism to maximize stability as this change has been found only in pregnant women with a fall history (McCrory et al., 2013). Compared to non-fallers, pregnant fallers demonstrate a significant reduced impulse of the feet in the anterior-posterior (A-P) direction during descending. This may facilitate a more controlled movement of the heavier body to the next step and may avoid a rapid push off in the forward direction (McCrory et al., 2013).

Apart from adaptive changes in ground reaction forces, Wu et al. (2004) established a simultaneous reduction in the transverse rotation amplitude of the pelvis and the thorax during treadmill walking in 13 pregnant women in the LP. The simultaneous change in both body segments is believed to reflect a synchronized segmental coordination. As this effect only occurs during pregnancy but not in the PP (Gilleard and Brown, 1996), it seems likely that the synchronized pelvic-thoracic movement counteracts the increased BM during pregnancy. This assumption is confirmed by Ogamba et al. (2016) who have also observed synchronized pelvic-thoracic movements in non-pregnant women walking with a 9.07 kg anterior pseudo-pregnancy sac.

Pregnant women have further been found to unconsciously lean their trunk in the lateral direction towards the supporting leg (Krkeljas, 2018) which is associated with the commonly-reported waddling gait in pregnant women (Hagan and Wonh, 2010; Wu et al., 2004; Foti et al., 2000). Waddling during pregnancy may be related to the increased step width and a reduced use of the hip abductor muscles (Foti et al., 2000; Mei et al., 2018; Bird et al., 1999; Branco et al., 2014). Trunk lean in the coronal plane is assumed to minimize the moment arm and, thus, to increase the effort of the hip adductor muscles (Krkeljas, 2018).

Pregnancy also leads to trunk lean in the sagittal plane that is associated with an increased abdominal mass (see chapter 2.2.1). This effect, however, has only been established in static conditions during motionless standing (Krkeljas, 2018). During walking the posture of the trunk is not affected by the increased abdominal mass in either pregnant women (Krkeljas, 2018) or in non-pregnant women wearing a 9.07 kg pseudo-pregnancy sac (Ogamba et al., 2016).

As the demand of the hip abductor muscles increases in the stance phase during walking due to the increased BM, pregnant women may respond with an increased double support time to minimize the time for single-limb support (Foti et al., 2000). Other mechanisms to compensate the increased mass may manifest such as decreased hip and knee extension (Huang et al., 2002; Branco et al., 2014) accompanied by a smaller step length (Mei et al., 2018; Branco et al., 2014). Some women demonstrate increased hip extension during walking (Huang et al., 2002). This change, however, is frequently accompanied by sacroiliac pain (Huang et al., 2002).

Apart from stability enhancing strategies, pregnant women have further been found to demonstrate a 5 ° reduced ankle dorsiflexion during barefoot walking (Hagan and Wonh, 2010). Changes in gait pattern are also assumed to involve an increased use of the plantarflexors which is necessary to facilitate lifting of the heavier body in the forward direction (Foti et al., 2000). As stated by Foti et al. (2000) this may, however, lead to an increased muscular demand on the calves that is associated with the high prevalence of cramps in pregnant women (Hagan and Wonh, 2010; Foti et al., 2000; Ireland and Ott, 2000).

Summing up, pregnancy is accompanied by numerous alterations in gait pattern (Bertuit et al., 2015; Ribeiro et al., 2011; Forczek and Staszkiewicz, 2012; Mei et al., 2018; Branco et al., 2014). Some of these alterations such as reduced step length, slower gait velocity, and increased step width are likely to reflect stability enhancing strategies in order to improve the safety of the heavier body during locomotion (Branco et al., 2014; Lymbery and Gilleard, 2005; Mei et al., 2018; Ribeiro et al., 2011). Alterations such as the increased double support time and the reduced single support time may additionally point towards adaptations to minimize the musculoskeletal demand that increases with the heavier body (Forczek and Staszkiewicz, 2012; Mei et al., 2018; Branco et al., 2014; Bertuit et al., 2015).

2.2.3 Balance

Evidence from several studies revealed that pregnancy is also likely to affect balance ability (Butler et al., 2006; Cakmak et al., 2014; Inanir et al., 2014; Jang et al., 2008). While changes in postural stability seem to be small and physiologically irrelevant in the EP (Butler et al., 2006; Inanir et al., 2014), substantial impairments have been detected in T2 and T3 (Inanir et al., 2014; Jang et al., 2008; Butler et al., 2006; Nagai et al., 2009; Ribas and Guirro, 2007).

Several studies analyzed postural stability in pregnant women in static conditions assessing CoP movements during motionless standing on a force plate (Butler et al., 2006; Jang et al., 2008; Nagai et al., 2009; Opala-Berdzik et al., 2014, 2015; Oliveira et al., 2009). The findings from these studies are inconsistent and differ greatly depending on the analyzed parameters. While Nagai et al. (2009) reported a larger A-P sway path in pregnant women in the 30^{th} WoP compared to non-pregnant women, another research group did not establish any differences in this sway parameter between the advanced stage of pregnancy and PP (Opala-Berdzik et al., 2014). Butler et al. (2006) described a significant larger sway velocity in T2 and T3 compared to non-pregnant women. In contrast, other authors did not detect any differences between a pregnant and non-pregnant group (Jang et al., 2008) or the same women during and after pregnancy (Opala-Berdzik et al., 2014).

Inanir et al. (2014) conducted dynamic measures in pregnant and non-pregnant women during bipedal standing using a Biodex Balance System with an inclinable platform (see chapter 4.2). The results of the overall balance ability scores demonstrated a significant decline in dynamic stability in T3. Another research group using the same measurement device, however, did not observe any changes in the balance scores (Cakmak et al., 2014). The latter findings are likely to reflect observations by McCrory et al. (2010b) assessing A-P sway in response to translational perturbations during bipedal standing on a movable force plate in 41 pregnant and 40 non-pregnant women. The A-P sway in pregnant women was not significantly different from the non-pregnant women. There were also no differences between the groups for different perturbation amplitudes (small, medium and large) or perturbation directions (forward and backward) (McCrory et al., 2010b).

While studies consistently report balance changes for the sagittal plane (Jang et al., 2008; Nagai et al., 2009; Ribas and Guirro, 2007; Opala-Berdzik et al., 2015), the coronal plane has been described to require further research (Branco et al., 2014). Jang et al. (2008), however, state that the coronal plane seems likely to be less affected by pregnancy as impairments can more easily be compensated by a wider stance width (Jang et al., 2008; Opala-Berdzik et al., 2015; Lymbery and Gilleard, 2005; Oliveira et al., 2009). A similar compensatory mechanism for the sagittal plane has not yet been established.

Further research on pregnant women focuses on the effect of visual input on postural stability (Oliveira et al., 2009; Nagai et al., 2009; Butler et al., 2006; Opala-Berdzik et al., 2015). In a study by Oliveira et al. (2009), 20 pregnant women were instructed to stand on a force plate as motionless as possible with their eyes opened and closed. The sway area significantly increased in T2 and T3 for the eyes closed condition. These findings indicate that women in the advanced stage of pregnancy rely more heavily on visual cues for balance control (Oliveira et al., 2009). Similar results have been observed by Opala-

Berdzik et al. (2015) who also report an increase in the A-P sway path and velocity in the eyes closed condition from the EP to LP.
In contrast, Nagai et al. (2009) suggest that reliance on visual cues during pregnancy is less important than reliance on somatosensory input. The authors analyzed M-L postural sway data from pregnant and non-pregnant women. Irrespective of whether eyes were open or closed, the power spectrum of the pregnant group demonstrated reduced frequencies larger than 1 Hz. As frequencies larger than 1 Hz are generally stabilized by somatosensory input, the results indicate that for balance maintenance during pregnancy, women receive input from somatosensory sources more intensively than non-pregnant women.

It remains debatable whether postural stability remains diminished in the PP. Opala-Berdzik et al. (2015) detected a significant improvement in postural sway two months postpartum. In contrast, Butler et al. (2006) reported a significant impairment in postural sway six to eight weeks postpartum (Butler et al., 2006). Jang et al. (2008) found that impairments in M-L postural sway remain even six months after childbirth.

In conclusion, there is evidence to suggest that pregnancy leads to impairments in static and dynamic postural stability in the advanced stages of pregnancy (Butler et al., 2006; Cakmak et al., 2014; Inanir et al., 2014; Jang et al., 2008). The findings from the studies, however, are inconsistent and differ depending on the analyzed balance parameters (Nagai et al., 2009; Opala-Berdzik et al., 2014; Butler et al., 2006). Impairments in postural stability have been found to primarily occur in the sagittal plane (Jang et al., 2008; Nagai et al., 2009; Ribas and Guirro, 2007; Opala-Berdzik et al., 2015). The coronal plane is less likely to be affected as an increased stance width may compensate for instability in the lateral direction (Jang et al., 2008). Balance control in the advanced stages of pregnancy is associated with an increased reliance on visual cues (Oliveira et al., 2009; Nagai et al., 2009; Butler et al., 2006; Opala-Berdzik et al., 2015). However, another study found that pregnant women rely more heavily on somatosensory input in this time period (Nagai et al., 2009). There is disagreement about whether a decline in balance performance during pregnancy is accompanied by long-term effects in the PP (Opala-Berdzik et al., 2015; Butler et al., 2006; Jang et al., 2008).

2.3 Psychological changes

In addition to physical and hormonal changes, pregnancy has also been shown to affect the mental state (Nagai et al., 2009; Bjelica et al., 2018; Dennis et al., 2017; Nakic Rados et al., 2018). Pregnancy, and especially the first one, is believed to be an enormous psychological experience during which the woman is confronted with an entirely new situation (Bjelica et al., 2018). On the one hand pregnancy is associated with a period of maturity of the woman's personality (Bibring and Valenstein, 1976). On the other hand pregnancy characterizes a state of mental tension involving feelings of uncertainty, fear of losing identity as well as a number of worries regarding the course and outcome of pregnancy (Bjelica et al., 2018; Dennis et al., 2017; Nakic Rados et al., 2018). Mental tension in a pregnant woman occurs consciously or unconsciously (Bjelica et al., 2018). It is commonly demonstrated through vulnerability, frequent mood changes, ambivalence, and anxiety (Bjelica et al., 2018).

Anxiety during pregnancy occurs in combination with depressive symptoms (Dennis et al., 2017; Nakic Rados et al., 2018) affecting 18 - 25 % of women (Dennis et al., 2017; Nakic Rados et al., 2018). The prevalence significantly increases over the course of the different stages of pregnancy and increases in the PP by 15 - 33 % (Dennis et al., 2017; Nakic Rados et al., 2018). The risk of suffering from anxiety symptoms even one year after delivery has been found to be 9 % (Dennis et al., 2017).

Changes in the mental state during pregnancy such as increased anxiety are frequently accompanied by an unhealthy maternal behavior such as a reduced participation in prenatal care or insufficient low weight gain during pregnancy (Dayan et al., 2002). These factors negatively affect the fetal development and the birth outcome (Ding et al., 2014). Maternal anxiety has also been found to be accompanied by long-lasting consequences for the newborn that can manifest as impaired mental development at the age of 2 years (Brouwers et al., 2001). It further increases the risk of attention deficit hyperactivity disorder in 8 - 9 year old children (Van den Bergh and Marcoen, 2004) and of cognitive disorders during adolescence (Van den Bergh et al., 2005).

Depressive symptoms and bad mood during and after pregnancy is associated with changing hormone levels of progesterone and testosterone (Buckwalter et al., 2001). Increased levels of progesterone during pregnancy are primarily responsible for the uterine quiescence and the prevention of the rejection of the embryo (Dante et al., 2013). However, this hormone is likely to negatively affect mood in pregnant women (Buckwalter et al., 2001). Similarly, high levels of testosterone are assumed to worsen mood in the PP (Buckwalter et al., 2001).

Summing up, pregnancy is associated with changes in the mental state that are partly attributed to fluctuating hormone levels (Buckwalter et al., 2001). Changes in the mental state are commonly observed through increased anxiety levels (Bjelica et al., 2018) that affect around one-third of women during and after pregnancy (Dennis et al., 2017; Nakic Rados et al., 2018). While anxiety during pregnancy negatively affects birth outcome (Dayan et al., 2002), it has also been shown to contribute to the development of mental and cognitive disorders in newborns (Van den Bergh and Marcoen, 2004; Van den Bergh et al., 2005; Brouwers et al., 2001; Ding et al., 2014).

3 Risk of injury during pregnancy

As outlined in the previous chapter, pregnancy is accompanied by several morphological, functional and psychological changes. Some of these changes are assumed to increase the number of falls and the risk of injury in pregnant women while also negatively affecting the exercise routine.

Following a short introduction on the prevalence of falls in pregnant women, this chapter provides information on potential fall risk factors that are discussed in the literature.

3.1 Prevalence of falls during pregnancy

Around 2 - 5 % of women experience an injury during pregnancy (Harland et al., 2014; Vladutiu et al., 2010). Falls are the primary mechanism of injury at 63 % (Harland et al., 2014). In a large cohort study of 3,997 pregnant women, the incidence of falls was found to be 27 % (Dunning et al., 2010). The highest number of falls at 61 % was detected between the fifth and seventh months of pregnancy (Dunning et al., 2003; McCrory et al., 2010b). This indicates that pregnant women are more likely to fall in the second half of pregnancy.

According to Dunning et al. (2010), around 35 % of 1070 pregnant fallers fell twice or more during pregnancy. Many falls are associated with locomotion (Vladutiu et al., 2010; Dunning et al., 2010; Krkeljas, 2018) such as walking on slippery floors, uneven grounds, and in poorly lit environments (Dunning et al., 2010). Falls are also associated with stair climbing (Dunning et al., 2010) with a higher number of falls being reported for descending than ascending (McCrory et al., 2013). For 35 % of pregnant fallers, medical attention is needed, while for 11 % of fallers a hospital admission is necessary (Dunning et al., 2010).

Compared with values from the literature, the reported incidence of falls in pregnant women at 27 % (Dunning et al., 2010) is similarly high to the incidence of falls described for the elderly (Campbell et al., 1990). However, this number has never been contrasted with a reference value from a non-pregnant control group or the same group during another period of time, e.g. after delivery. As stated by McCrory et al. (2010b), this limitation should be considered when interpreting the results.

In one study by Jang et al. (2008) that determined the incidence of falls in 15 pregnant women, a control group was involved. Only two (13 %) of the 15 pregnant participants fell. In contrast, a higher percentage of falls occurred in the controls at 47 %.

The available literature illustrates that the risk of falling in pregnant women is not sufficiently investigated. Nevertheless, pregnancy is assumed to be associated with an increased number of falls (Dunning et al., 2003; McCrory et al., 2010b). Evidence from one study reveals that fall incidence in pregnant women is similarly high to the fall incidence in seniors (Dunning et al., 2010; Campbell et al., 1990). More than one-third of fallers expect more than one fall (Dunning et al., 2010). Falls primarily occur during locomotion and can be accompanied by meaningful health consequences (Dunning et al., 2010).

3.2 Risk factors

3.2.1 Weight gain

Weight gain during pregnancy is commonly described to be the primary factor influencing the risk of falling when exercising (Artal and O'Toole, 2003; Inanir et al., 2014; Jang et al., 2008; Nagai et al., 2009). The increased anterior mass on the trunk and the changed body shape are accompanied by a changed body posture (Opala-Berdzik et al., 2010) manifesting as a posterior shift of the CoM and an increased lumbar lordosis (see chapter 2.2.1). These changes are frequently assumed to negatively affect balance control (Artal and O'Toole, 2003; Inanir et al., 2014; Jang et al., 2008; Nagai et al., 2009). However, a recent study did not detect any association between impairments in postural stability and the gained weight during pregnancy (Butler et al., 2006).

The absolute BM is also unlikely to be related to the incidence of falls in pregnant women even though the highest number of falls has been detected in the LP when the BM is greatest (McCrory et al., 2010b). Research by McCrory et al. (2010b) and Ersal et al. (2014) clarified that the absolute BM of pregnant fallers is not significantly different to that of pregnant non-fallers.

It can be summarized that the available evidence (McCrory et al., 2010b; Ersal et al., 2014; Butler et al., 2006) is likely to contradict the often-stated assumption that weight gain during pregnancy may lead to impairments in balance ability and an increased risk of falling in pregnant women (Artal and O'Toole, 2003; Inanir et al., 2014; Jang et al., 2008; Nagai et al., 2009).

3.2.2 Loss in muscle strength

A loss in peripheral muscle strength has also been deemed to be an important contributor to falls in pregnant women (Moreland et al., 2004; McCrory et al., 2010b; Opala-Berdzik et al., 2014; McCrory et al., 2010a). However, the number of studies on peripheral muscle properties is rare, as most studies focused on changes in the abdominal muscles and pelvic floor muscles due to an increased risk of incontinence among pregnant women (Morkved et al., 2004; Gameiro et al., 2011; Smith et al., 2007). There is evidence to suggest that the upper extremities' strength decreases by 9 % from the middle stage of pregnancy to the LP (Atay and Basalan Iz, 2015). A much larger loss of 24 % has been reported for the lower extremities (Treuth et al., 2005). The latter finding, however, is likely to mainly reflect changes during the recovery phase after delivery as the authors only performed the measurements before pregnancy and six weeks postpartum. Thus, there is so far no evidence to suggest that pregnancy actually leads to muscle weakness in the lower extremities.

While a substantial increase in the research of pregnancy-associated changes in the lower extremities' muscle strength is required, pregnancy is well known to diminish the force production of the abdominal muscles (Gilleard and Brown, 1996). With the growing uterus, the orientation of the abdominal muscles alters (see chapter 2.1.3.1). This change is associated with an impaired stabilization of the pelvis (Gilleard and Brown, 1996) that may also negatively affect the overall postural stability and the number of falls (Cakmak et al., 2014).

A decline in postural stability may also be attributed to the diminished endurance of the back extensor muscles as it has been found in young healthy adults (Angyan et al., 2007). Noren et al. (2002) demonstrated that the endurance of the back extensor muscles in pregnant women is reduced by 60 % compared to non-pregnant women.

Muscle weakness during pregnancy may also partly be attributed to calcium deficiency.

Calcium deficiency is highly common in pregnant women and is associated with the high prevalence of leg cramps (Ireland and Ott, 2000; Hammar et al., 1981). In community-dwelling elderly, the long-term supplementation of calcium and vitamin D has been shown to improve quadriceps muscle strength and to significantly reduce the number of falls by 39 % (Pfeifer et al., 2009). The potential positive effects of calcium supplementation during pregnancy on the incidence of falls have not yet been discussed in the literature.

In conclusion, pregnancy is believed to be associated with a general loss of muscle strength that negatively affects balance control and the number of falls (Moreland et al., 2004; McCrory et al., 2010b; Opala-Berdzik et al., 2014; McCrory et al., 2010a). While pregnancy is likely to lead to a weakness of the abdominal muscles, the back extensors and the upper extremities (Moreland et al., 2004; McCrory et al., 2010b; Opala-Berdzik et al., 2014; McCrory et al., 2010a; Gilleard and Brown, 1996; Noren et al., 2002; Gutke et al., 2008), there is so far no evidence to suggest that the properties of the lower extremities actually change during pregnancy. Thus, the assumed effect of leg weakness on balance impairments and falls in pregnant women needs to be further investigated.

3.2.3 Increased laxity of the connective tissue

Falls in pregnant women are further associated with an increased compliance of the ligaments in the pelvic area (Ritchie, 2003; Borg-Stein et al., 2005; Cakmak et al., 2014; Inanir et al., 2014). While increased pelvic laxity is essential to facilitate childbirth, laxity is at the same time believed to increase joint mobility which negatively affects the overall postural stability (Cakmak et al., 2014). In order to limit pelvic joint mobility and to improve postural stability in pregnant women, flexible and elastic maternity support belts (MSB, Figure 7) which are similar to kidney belts made out of an elastic cotton fabric have been suggested to stabilize the pelvis (Cakmak et al., 2014). Measurements on a Biodex Balance System (see chapter 4.2) demonstrated that the MSB significantly improves postural stability by 33 % (Cakmak et al., 2014). Also, the fall risk scores that are internally assessed by the system were significantly reduced when using the MSB, by 20 % in T1 and 32 % in T2 and T3, respectively. The mechanism behind this effect is unclear. However, there is evidence to suggest that other types of flexible and elastic belts significantly reduce the rotation movements of the pelvic joints around the transverse axis which enhances pelvic joint stability (Sichting et al., 2014; Vleeming et al., 1992).

Figure 7: Flexible and elastic maternity support belt (MSB)

Apart from the pelvic area, it is assumed that an increased compliance of peripheral ligaments and tendons during pregnancy negatively affects postural stability. While increased compliance of the ligaments is assumed to impair the stabilization of the joints, increased compliance of tendons is suggested to diminish motor control (Pearson et al., 2011) as well as postural reaction time (McCrory et al., 2010a) as this may increase the time for muscle fascicle shortening during force production. However, no study in humans has been found that actually investigated the effect of pregnancy-associated changes on the mechanical properties of the lower limbs' ligaments and tendons (see chapter 2.1.3.3 and 2.1.3.4).

Changes in the ligament and tendon mechanical properties are generally deemed to be related to changes in the endocrine system (Pearson et al., 2011; Dragoo et al., 2011a,b; Lubahn et al., 2006; Toth and Cordasco, 2001; Hansen et al., 2009; Maffulli et al., 1999). As seen in menstruating women, increased hRLX levels are accompanied by a reduction in patellar tendon stiffness (Pearson et al., 2011). As hRLX levels have been found to be ten times larger during pregnancy compared to non-pregnant women (MacLennan et al., 1986a), this effect may be potentiated in pregnant women.

The hormone hRLX is also assumed to be a possible contributor to the high prevalence of anterior cruciate ligament injury in females (Faryniarz et al., 2006; Dragoo et al., 2009). As shown in humans (Toth and Cordasco, 2001), but also animal models (Dragoo et al., 2009), the anterior cruciate ligament demonstrates a significant increased laxity when the tissue is treated with hRLX. This change is believed to indicate an increased risk of injury (Toth and Cordasco, 2001; Dragoo et al., 2011a). The hormone hRLX may, thus, be associated with a frequently-observed increase in peripheral joint laxity (Dragoo et al., 2011a,b; Lubahn et al., 2006). However, in pregnant women, most studies have failed to establish a relationship between these parameters (Schauberger et al., 1996; Marnach et al., 2003) (see chapter 2.1.3.3).

In pregnant as well non-pregnant women, elevated levels of estrogen have been found to play an explanatory role in the frequently-observed increase in knee joint laxity (Charlton et al., 2001; Lee et al., 2013; Shultz et al., 2005; Lee et al., 2014; Deie et al., 2002; Heitz et al., 1999). This evidence is likely to be confirmed by observations of oral contraceptive users where suppressed levels of estrogen, thus, do not change the laxity of the joint (Lee et al., 2014; Pokorny et al., 2000; Hicks-Little et al., 2007; Martineau et al., 2004). Oral contraceptive users have also been found to be less susceptible to ligament injuries than non-users (Moller Nielsen and Hammar, 1991; Rahr-Wagner et al., 2014; Gray et al., 2016). This may indicate an increased risk of ligament injuries when estrogen levels are elevated.

Increased levels of estrogen are additionally associated with an increased risk of tendon ruptures (Maffulli et al., 1999). It is known that giving postmenopausal women with low estrogen levels a large amount of estrogen (2 mg oral estradiol) increases tendon collagen turnover (Hansen et al., 2009) and leads to disorganized fiber structure (Cook et al., 2000) and a reduced formation of cross-links by inhibiting the responsible enzyme. It has also been found to cause a reduction in the achilles tendon CSA (Hansen et al., 2009). It may also be possible that increased levels of estrogen during pregnancy negatively affect the mechanical properties of the tendons thereby impairing postural stability.

In summary, falls and balance losses among pregnant women are believed to be associated with an increased laxity of ligaments and tendons (Pearson et al., 2011; McCrory et al., 2010a). This change is likely to be attributed to elevated levels of hRLX and estrogen during pregnancy (Dragoo et al., 2011a,b; Lubahn et al., 2006; Charlton et al., 2001; Lee et al., 2013; Shultz et al., 2005; Lee et al., 2014; Deie et al., 2002; Heitz et al., 1999). While an increased compliance of the ligaments is associated with an increased risk of connective tissue injuries and impaired stabilization of the joints (Ritchie, 2003; Borg-Stein et al., 2005; Cakmak et al., 2014; Inanir et al., 2014), reduced tendon stiffness may negatively affect motor control and postural reaction time in pregnant women (McCrory et al., 2010a; Pearson et al., 2011).

3.2.4 Anxiety and fear of falling

As 51 % of women report a fear of falling during pregnancy (Atay and Basalan Iz, 2015), Opala-Berdzik et al. (2010) speculated that the posterior shift of the CoM during pregnancy (see chapter 2.2.1) reflects a protective mechanism against falling and hurting the fetus. This assumption, however, is contradictory to observations in patients and elderly with balance impairments that move the CoM in the opposite direction (Blaszczyk et al., 2007; Woodhull-McNeal, 1992). In the event of balance perturbations, an anterior shift of the CoM may facilitate the easier stepping forward with one foot in order to increase the base of support and to regain stability (Opala-Berdzik et al., 2010; Thelen et al., 1997). The opposite phenomenon in pregnant women, however, seems unreasonable from an evolutionary perspective.

The posterior shift of the CoM may instead reflect a mechanism that compensates the increased anterior mass of the trunk and maintains a safe standing posture (Whitcome et al., 2007; Krkeljas, 2018; Östgaard et al., 1993; Dumas and Reid, 1997; Franklin and Conner-Kerr, 1998; Ireland and Ott, 2000). Further strategies such as a lower gait velocity, an increased stance width, and a reduced double support time during walking (Forczek and Staszkiewicz, 2012; Mei et al., 2018; Branco et al., 2014; Bertuit et al., 2015) as well as a more stable stance (McCrory et al., 2010b) and an increased ankle stiffness (Ersal et al., 2014) have been found to enhance stabilization of the heavier body during pregnancy and to prevent future falls.

However, despite several stability enhancing strategies, pregnant women have repeatedly been found to suffer from increased anxiety symptoms (Dennis et al., 2017; Nakic Rados et al., 2018; Bjelica et al., 2018) which significantly impair balance ability (Nagai et al., 2009). Nagai et al. (2009) analyzed differences in postural sway during motionless upright standing in 35 pregnant women with high and low anxiety levels. The negative effect of anxiety is manifested as an increased postural sway that was solely established in women with high anxiety levels. The mechanism behind this effect is unclear. However, there is evidence from other study populations to suggest that high anxiety levels are frequently accompanied by a decline in the somatosensory organization, an increase in latency for neuromuscular responses (Bolmont et al., 2002), and muscle weakness (Bartholomew et al., 2008). All these factors may be assumed to contribute to impaired postural stability in anxious pregnant women.

The negative effect of pregnancy on the mental state can, on the one hand, be improved upon participating in a regular aerobic exercise program (Robledo-Colonia et al., 2012; Vargas-Terrones et al., 2019). On the other hand, concerns about falling have been found to significantly reduce the physical activity level among pregnant women (Atay and Basalan Iz, 2015). As reduced physical activity is accompanied by a loss in muscle strength and potentially by impairments in balance ability (see chapter 3.2.2), concerns about falling may paradoxically increase the risk of falling.

Summing up, it is likely that pregnancy-associated changes in the mental state such as increased anxiety and fear of falling are relevant risk factors for impaired balance ability and falls in pregnant women (Nagai et al., 2009). It has further been stated that fear of falling leads to changes in body posture (Opala-Berdzik et al., 2010). However, further studies to clarify this effect are required.

4 Objective of the thesis

It is well established that women attain several benefits from physical activity during pregnancy (DeMaio and Magann, 2009; Vladutiu et al., 2010; Nascimento et al., 2012; Evenson et al., 2014; ACOG, 2015) (see chapter 1). However, the safety of physical activity has been questioned since physical changes during pregnancy are assumed to increase the risk of injury (see chapter 3.2). One of the changes that is frequently described in textbooks, pregnancy guidelines, and the media (Danning, 2013; Nordin and Frankel, 2001; Martin et al., 2015; Blott, 2010; Klausmann, 2002; Engels et al., 2009) is an increased laxity of peripheral ligaments and tendons that impairs joint stability and increases the risk of losing balance and falling (Ritchie, 2003; Borg-Stein et al., 2005; Cakmak et al., 2014; Inanir et al., 2014). However, this claim is based on assumptions as no study has ever demonstrated that the mechanical properties of human peripheral ligaments and tendons actually change during pregnancy.

As a significant percentage of pregnant women worldwide is not sufficiently active (Mudd et al., 2009; Dobson et al., 2012; Gaston et al., 2012; Gjestland et al., 2013; Juhl et al., 2012; Zhang and Savitz, 1996; Sternfeld et al., 1995), it is important to encourage pregnant women to continue exercising and to increase their activity levels. However, in order to reduce fears regarding injury when exercising, scientifically based recommendations and appropriate strategies for injury prevention are necessary.

Considering the outlined deficits on the research of risk factors related to pregnancy, one fundamental step is to gain a deeper understanding of the changes in musculoskeletal tissue properties. This doctoral thesis aims to make a contribution to closing this gap.

The doctoral thesis includes two parts. The first part focuses on the establishment of pregnancy-associated changes in the lower extremities' muscle-tendon unit, while the second part is related to a flexible and elastic MSB being a possible strategy to improve balance ability and to prevent falls in pregnant women.

4.1 Part 1: Changes in the muscle-tendon unit during pregnancy

Falls are the primary mechanism resulting in injuries in pregnant women (Harland et al., 2014) and are deemed to be attributed to the multiple changes that accompany pregnancy (see chapter 3.2). One of these changes is a loss in the lower extremities' muscle strength that is discussed as contributing factor as it may negatively affect postural stability (Moreland et al., 2004; McCrory et al., 2010b; Opala-Berdzik et al., 2014; McCrory et al., 2010a). However, the association between muscle weakness and the high incidence of falls in pregnant women is unclear, as no study has ever established a loss in the lower extremities' muscle strength during pregnancy (see chapter 3.2).

In contrast, there is evidence from studies (Falick Michaeli et al., 2015; Rundgren, 1974) describing conditions during pregnancy that may be favorable for retaining muscle strength. Hormonal changes during pregnancy, for example, may trigger muscle growth in the skeletal muscles as has been shown for the uterus muscle (Rundgren, 1974). Another study assessing the properties of injured hind limbs in gestating mice revealed that pregnancy improves the regeneration capabilities of skeletal muscles, thereby counteracting the negative effects of aging (Falick Michaeli et al., 2015).
The increased BM during pregnancy may also have an impact on the muscle growth of the leg muscles as they have to stabilize the gained weight in all trimesters of pregnancy. In a previous study in the elderly, it was established that weight gain is a sufficiently high stimulus to increase the anatomical CSA of the quadriceps femoris muscles (Delmonico et al., 2009).
In addition, the skeletal muscle properties may eventually be positively affected by water retention during pregnancy. In trained athletes, an increase in the TBW has been reported to contribute to an improved muscle performance (Judelson et al., 2007).

If pregnancy is truly accompanied by favorable metabolic conditions promoting the adaptation of muscles to training and mechanical loading (Falick Michaeli et al., 2015; Rundgren, 1974; Delmonico et al., 2009), e.g. an increased BM, it may also be conceivable that tendons of the lower body become stiffer during pregnancy. However, in textbooks, pregnancy guidelines, and the media, it is frequently stated that pregnancy leads to a reduction in tendon stiffness (Danning, 2013; Nordin and Frankel, 2001; Martin et al., 2015;

Blott, 2010; Klausmann, 2002; Engels et al., 2009). This change is believed to increase the risk of connective tissue injuries (Blott, 2010; Klausmann, 2002; Lutter and Lee, 1993; Kiechle, 2011; Engels et al., 2009; Eberlein, 2008; Drewes, 2011) and falling in pregnant women (Ritchie, 2003; Borg-Stein et al., 2005; Cakmak et al., 2014; Inanir et al., 2014). On the one hand, there is no evidence to suggest that tendon stiffness actually decreases during pregnancy. On the other hand, from a previous study in menstruating women it is known that increased levels of hRLX is accompanied by reduced patellar tendon stiffness (Pearson et al., 2011). As hRLX levels during pregnancy are ten times greater than in non-pregnant women (MacLennan et al., 1986a), this effect may be potentiated in pregnant women.

With regard to the lack of evidence for pregnancy-associated changes in the musculoskeletal tissue we intended to provide initial information on the effect of pregnancy on the functional, morphological, and mechanical properties of the muscle-tendon unit of the knee joint. In this part of the thesis we published two research articles. The first is related to the establishment of changes in muscle properties during pregnancy. In the second research article, pregnancy-related changes in the tendon properties are addressed.

First research article:
The purpose of this study was to longitudinally investigate the properties of the knee extensors in the EP and LP as well as six months postpartum. The postpartum values were compared to non-pregnant controls. We hypothesized 1) that knee extensor muscle strength, thickness, and pennation angle will increase in the LP due to the increased BM, and 2) that with a reduction in BM in the PP the values will return to pre-pregnancy levels and not be significantly different from the non-pregnant controls. As a potential increase in muscle thickness may be attributed to BM as well as water retention during pregnancy, we further hypothesized 3) that changes in muscle properties are related to changes in BM and body composition (Bey et al., 2019b).

Second research article:
With this study we aimed to longitudinally investigate the mechanical properties of the patellar tendon. Again, the measurements were conducted in the EP and LP as well as

six months after delivery. The postpartum values were also compared with values from a non-pregnant control group. We hypothesized that patellar tendon stiffness decreases during pregnancy (Bey et al., 2019a).

4.2 Part 2: The effect of a maternity support belt on static postural stability during pregnancy

While pregnancy is assumed to reduce muscle strength and to increase the compliance of the connective tissue, these changes are likely to impair joint stability (see chapter 3.2.3). As diminished joint stability may further negatively affect the overall postural stability and the incidence of falls in pregnant women, some efforts have been made to find appropriate strategies to enhance joint stability. While in general primarily time-consuming exercise intervention strategies are suggested to strengthen the surrounding muscles of the joints (Lewkonia, 1987), for pregnant women simple tools such as braces and support bandages have been proposed to stabilize the joints (Cakmak et al., 2014; Ersal et al., 2014). One of them is an MSB (see chapter 3.2.3) which limits pelvic mobility (Cakmak et al., 2014). There is evidence from one study by Cakmak et al. (2014) that suggests that this belt increases postural stability in pregnant women. The MSB is further postulated to prevent falls during pregnancy (Cakmak et al., 2014).

In that study, the MSB effect on postural stability was assessed by applying the novel Biodex Balance System in dynamic conditions (Cakmak et al., 2014). The Biodex Balance System is a device with an inclinable platform that provides balance ability scores and fall risk scores based on normative data and medical protocols. However, more commonly-used balance tests in static conditions (Moreno Catala et al., 2015; Hamed et al., 2018; Opala-Berdzik et al., 2014; Nagai et al., 2009) such as postural sway during motionless bipedal standing on a force plate would enable a comparison with findings from other studies.
As body shape is primarily affected in the sagittal plane during pregnancy, measurements during forward and backward leaning may further help to reveal possible impairments in the anterior and posterior limits of stability (LoS).
Finally, it is common that studies on pregnant women do not involve a control group with

non-pregnant women (Opala-Berdzik et al., 2010, 2015; Oliveira et al., 2009). This limits a comprehensive interpretation of the data. Similarly, Cakmak et al. (2014) investigated the effect of an MSB on postural stability and the incidence of falls by obtaining data from a group of pregnant women. Thus, further studies should consider a study population with pregnant and non-pregnant women to facilitate comparisons with a reference value.

As a flexible and elastic MSB has not yet sufficiently been investigated to be a suitable method for fall prevention in pregnant women, with our third research article we pursued the objective of analyzing the effect of an MSB on static postural stability in pregnant and non-pregnant women thereby investigating postural sway and LoS.

Third research article:
The purpose of this study was to investigate the effect of an MSB on static postural stability assessing postural sway and LoS. This issue has been addressed within a cross-sectional design comparing the static postural stability of women in the different trimesters of pregnancy. Considering a control group with non-pregnant women facilitated a more comprehensive interpretation of the data. We hypothesized that postural stability in pregnant women can be improved using an MSB (Bey et al., 2018).

5 First article | Vastus Lateralis Architecture changes during Pregnancy – A longitudinal Study

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5.1 Abstract

While the incidence of falls has been described to increase with pregnancy, the mechanism behind this is unclear. Pregnancy-associated changes in lower extremity muscle strength could be a possible factor influencing injury risk. Thus, the aim of this longitudinal study was to investigate muscle strength and architectural properties of the lower limbs in different stages of pregnancy and postpartum.

In 19 pregnant women (30 $\pm$ 4 years) and 15 non-pregnant controls (28 $\pm$ 4 years) muscle strength and architectural properties of the vastus lateralis muscle were assessed combining dynamometry, ultrasound, kinematic, and electromyographic (EMG) measurements. BM and body composition were determined using bioimpedance analysis. In the pregnant women, the measurements were conducted in the 16 $\pm$ 4^{th} (EP) and 29 $\pm$ 4^{th} WoP (LP) as well as in the 32 $\pm$ 9^{th} week postpartum (PP).

Muscle thickness and pennation angle of the fascicles significantly increased in the LP, while muscle strength remained constant during and after pregnancy. BM, skeletal muscle mass (SMM), FM, ICW, and ECW also peaked in the LP. Postpartum values did not differ from the controls. Changes in the muscle properties were not related to changes in BM and body composition.

Conditions during pregnancy promote changes in the vastus lateralis architecture indicating muscle hypertrophy. However, pregnancy did not increase muscle strength while BM progressively increases. Therefore, in the event of balance perturbations pregnant women may not be able to meet the requirements for the increased physical demand.

Keywords:
muscle architecture, muscle growth, muscle strength, hypertrophy, body composition, exercise, injury, pregnancy

5.2 Introduction

Positive effects of exercise during pregnancy are well documented. Thus, regular exercise during pregnancy is recommended to reduce pregnancy-associated symptoms such as hypertension or gestational diabetes, as well as to maintain muscle strength and endurance to prepare for delivery (Vladutiu et al., 2010; Nascimento et al., 2012). However, the safety of exercise during pregnancy has been questioned, as pregnant women are predisposed to falls (Dunning et al., 2003; Inanir et al., 2014). The incidence of falls in pregnant women has been reported to be 27 %, which is similar to the incidence of falls occurring in the elderly (Dunning et al., 2010). Physical changes during pregnancy such as weight gain and the changed body shape have been assumed to influence the risk of falling. In addition, pregnant women have repeatedly been observed to suffer from reduced static and dynamic postural stability compared to non-pregnant women (Oliveira et al., 2009; Inanir et al., 2014; Bey et al., 2018). These impairments in stability are assumed to contribute to the increased number of falls (Inanir et al., 2014).

Hormonal changes during pregnancy are reported to partially account for the decline in stability. The increased hRLX levels, for example, has been described to increase the compliance of the pelvic ligaments (Young, 1940) which may lead to joint instability.

Changes in the properties of peripheral skeletal muscles may also affect postural stability and injury risk. A loss in muscle strength, especially of the lower extremities, has been found to be associated with the incidence of falls in the elderly (Moreland et al., 2004). In pregnant women, the evidence for changes in the peripheral skeletal muscles is rare, since most studies mainly focused on muscle strength of the pelvic floor muscles and abdominal muscles due to the increased risk of incontinence during pregnancy (Morkved et al., 2004; Smith et al., 2007; Gameiro et al., 2011). To our knowledge, there are only two studies investigating changes in strength of the upper and lower extremities with pregnancy. One study investigated changes in the hand grip strength in pregnant women, detecting a 9 % loss in strength in the LP compared to the middle stage of pregnancy (Atay and Basalan Iz, 2015). Another study conducted measurements of the lower and upper body strength before pregnancy and 6 weeks postpartum (Treuth et al., 2005). These authors also established a loss in strength, with the largest loss occurring in the lower body with

24 %. However, the authors did not include measurements during pregnancy. Therefore, the results are more likely to reflect the changes during the recovery phase after childbirth than changes during pregnancy. The described loss in muscle strength in pregnant women may be related to the progressive increase in FM (Taggart et al., 1967). An increase in FM is known to reduce the desire for spontaneous physical activity (Brown, 2008), which, in turn, leads to muscle weakness (Atay and Basalan Iz, 2015).

Although these studies suggest that pregnancy is associated with muscle weakness, hormonal changes during pregnancy can also lead to muscle growth as it has been shown for the uterus muscle (Rundgren, 1974). Since pregnancy has been shown to improve the regenerative processes in skeletal muscles (Falick Michaeli et al., 2015), skeletal muscles of pregnant women may respond well to anabolic stimuli such as increased loading. As an increased BM has been found to increase the anatomical cross-sectional area of the quadriceps femoris muscle (Delmonico et al., 2009), the progressive increase in BM during pregnancy may potentiate the effect to trigger radial muscle growth in the lower extremities. Muscle strength during pregnancy may also be affected by water retention, which is a common side effect occurring with pregnancy (Lukaski et al., 1994; Valensise et al., 2000). While we know that TBW content affects muscular performance with a reduction in TBW being associated with a reduction in muscle strength (Judelson et al., 2007), it has not yet been investigated how or if muscle performance in pregnant women is affected by pregnancy-associated water retention.

In the event of pregnancy-associated reductions in muscle strength these would likely affect the injury risk during exercise as well as during daily activities. However, the lack of studies investigating pregnancy-related changes in peripheral skeletal muscle properties does not allow drawing clear conclusions. To be able to develop effective and safe interventions for pregnant women, similar to the strategies for addressing muscle strength and postural stability to reduce the risk of falls in the elderly (Moreland et al., 2004), the effect of pregnancy on skeletal muscles needs to be clarified.

Therefore, the aim of this longitudinal study was to investigate muscle properties of the knee extensors at two stages of pregnancy and six months after delivery.

We hypothesized that knee extensor muscle strength, thickness, and pennation angle will increase in the LP due to the increased BM. We hypothesized furthermore, that with a reduction in BM in the PP values will return to pre-pregnancy levels and not be significantly different from the non-pregnant controls. In addition, increases in muscle thickness may be affected by water retention. Thus, we further hypothesized that changes in muscle properties are related to changes in BM and body composition.

5.3 Materials and Methods

5.3.1 Participants

Muscle properties, BM and body composition during and after pregnancy were analyzed longitudinally in 19 pregnant women (30 ± 4 years). Due to the lack of longitudinal data on changes in muscle properties in pregnant women we were not able to conduct an a priori power analysis to determine the sample size. However, previous studies in our department have shown that this sample size is sufficient to detect training induced changes in the vastus lateralis muscle such as significant increases in muscle strength (8 %, $p = 0.003$) and thickness (24 %, $p < 0.001$) (Mersmann et al., 2016). All women were healthy without any orthopedic or pregnancy-associated disorders. Pregnant women with a multiple pregnancy were excluded from the study. The participants attended three experimental sessions in different stages of pregnancy: the first measurement was conducted in the EP (16 ± 4^{th} WoP), the second measurement in the LP (29 ± 4^{th} WoP) and the third measurement at least six months postpartum (PP, 32 ± 9 weeks after delivery) to reflect the non-pregnant status. In two of the pregnant women an additional measurement had been conducted prior pregnancy.

In order to compare the postpartum status of the pregnant women with data of non-pregnant controls an additional cohort of 15 healthy non-pregnant women (28 ± 4 years) was recruited. For the non-pregnant group, the same data were collected as for the pregnant group, while the measurements in the non-pregnant group were conducted once. Within this research project further data such as tendon properties were obtained and published as separate article (Bey et al., 2019a).

5.3.2 Measurement of Muscle Properties

To assess the muscle strength of the knee extensors and the architecture of the vastus lateralis muscle the women were seated on a dynamometer (BIODEX Medical System 3, Shirley, NY, United States). In order to monitor the knee joint angle and to precisely calculate the knee extensor moment (Arampatzis et al., 2004) kinematic measures were performed using seven Vicon cameras (VICON Motion Systems, version 1.7.1, Oxford, United Kingdom) at a frame rate of 250 Hz.

For data capturing five reflective markers were placed at the trochanter major, the lateral and medial epicondyle of the femur as well as the lateral and medial malleolus of the dominant leg. Standing barefoot in an upright body position with straight legs the vertical connection between the trochanter major and the lateral epicondyle was marked on the skin using a non-permanent marker. The length of the line was defined as the length of the femur. After marking the half of the femur length with a horizontal line the thigh perimeter was measured directly above the intersection of both lines. Subsequently, the participants took a seat on the dynamometer with an 85 ° trunk angle.

5.3.2.1 Muscle Strength

To examine muscle strength the women completed five trials of slow isometric ramp contractions with a 90 ° knee joint angle. Muscle strength was assessed determining the knee joint moment on the dynamometer. Gravitational forces as well as a misalignment between the knee joint and the dynamometer axis during the contractions have been reported to lead to overestimation of the knee joint moment of up to 17 % (Arampatzis et al., 2004). In order to consider this we conducted simultaneous measurements of kinematic and dynamometric data during the ramp contractions. The corrected knee joint moment was calculated through inverse dynamics (Arampatzis et al., 2004). Furthermore, since the contribution of the knee flexors has been found to affect the knee extensor moment by 6 % (Mademli et al., 2004), we additionally subtracted the knee flexor moment from the corrected knee joint moment. The knee flexor moment was assessed by EMG based estimates of the knee flexors' co-activation (Mademli et al., 2004). Details of the correction procedures have been described in previous studies (Arampatzis et al., 2004; Mademli et al., 2004; Bey et al., 2019a).

The relative knee joint moment was calculated normalizing the absolute knee joint moment to the BM. In two women of the control group we were not able to analyze the muscle strength due to an inadequate recording of the knee joint moment.

5.3.2.2 Architecture of Vastus Lateralis Muscle

To assess architectural properties of the vastus lateralis muscle the knee joint was flexed to 60 °. A 10 cm ultrasound transducer (7.5 MHz, My Lab60, Esaote, Genova, Italy) was positioned longitudinally to the muscle. A custom made plastic cast around the transducer with a ∼ 2.5 cm width on the long sides prohibited a possible tilt of the probe during measurement. One long side of the cast was positioned on the connecting line between trochanter major and lateral epicondyle with the middle of the transducer being placed at the middle of the femur. In this position, two ultrasound videos were captured at 25 Hz while the participants were instructed to keep their leg muscles relaxed.

In ten consecutive frames of each video the upper and deeper aponeurosis were manually traced using a custom written Matlab interface (Marzilger et al., 2018). Muscle thickness was determined calculating the distance between the aponeuroses. Visible snippets of inter-fascicular collagen were semi-automatically detected by the program, and a reference fascicle was generated based on the different characteristics of the snippets. The pennation angle and fascicle length (FL) were calculated from the reference fascicle in respect to the aponeuroses. FL in the pregnant women was reported as absolute values. To compare the pregnant to the non-pregnant group, FL was normalized to the femur length (FL_{norm}) to account for differences in body height (Table 1) between these groups.

5.3.3 Bioelectrical Impedance Measurement

To assess the body composition a bioelectrical impedance analysis was performed using the InBody 720 (Biospace Co., Korea). Measurements were conducted according to the manufacturer's guidelines. Immediately prior stepping on the scale the hand and foot electrodes were cleaned with an antibacterial tissue. Subsequently, the participants stood barefoot and lightly dressed on the scale. Each foot was placed on one heel and one forefoot electrode. The participants were instructed to grab the handles and to touch the two hand electrodes with the thumb and the four fingers. During the measurement the participants stood motionless with a straight body posture and the arms slightly abducted. Impedance values were produced from six different frequencies, from which the resistance of the trunk, the arms, and the legs was calculated. To assess changes in body composition the components BM, SMM, and FM in kilogram as well as the TBW, the ICW and ECW in liter were analyzed. Accuracy and test-retest reliability for body composition estimations have previously been reported (Lukaski et al., 1986; Lukaski and Bolonchuk, 1988; Kim and Kim, 2013; Legerlotz et al., 2018).

5.3.4 Statistical Analysis

Normality of the standardized residuals of all investigated parameters were tested in SPSS (Version 21, 32 Bit, IBM, United States) using the Shapiro-Wilk test. A one-way repeated measures ANOVA was performed to analyze differences between the time-points EP, LP, and PP, thereby considering the assumption of sphericity. In case of violations of sphericity the Greenhouse-Geisser correction was used. For post hoc comparisons between the measurement time points EP, LP, and PP paired t-tests with Bonferroni adjustment were performed. For pairwise comparisons of the not normally distributed parameters (BM at PP, BMI at PP, FL in the LP and PP, thickness at PP, pennation angle in the EP as well as FM in the LP and PP) the Friedman's test and the Wilcoxon signed-rank test were conducted.

Differences between the postpartum measures and the non-pregnant controls were analyzed using an independent samples t-test. The not normally distributed parameters (BMI, SMM, FM, TBW, and ECW for the controls and the above mentioned not normally distributed parameters for the pregnant group) were tested with the Mann-Whitney U-test. For the normally distributed data the effect size was assessed using Cohen's d. For the not normally distributed data the effect size r was calculated dividing the z-scores of the non-parametric tests by the square root of the number of total observations. Thereafter, r was converted into d.

To investigate the relationship between the muscle properties and body composition parameters we analyzed the Pearson correlation coefficients. The level of significance was set at $\alpha = 0.05$.

5.4 Results

5.4.1 Anthropometric Measures

As expected, BM (Figure 8A), BMI, and the thigh perimeter (Table 1) significantly increased from the EP to LP (d_{mass} = 3.29, p < 0.001; d_{BMI} = 3.65, p < 0.001; $d_{perimeter}$ = 0.485, p < 0.001) and significantly dropped after delivery (d_{mass} = 2.88, p < 0.001; d_{BMI} = 2.88, p < 0.001; $d_{perimeter}$ = 0.746, p < 0.001). BM, BMI, and the thigh perimeter in the PP were not different from the non-pregnant controls (p > 0.05). Body height and age in the pregnant women (Table 1) were significantly higher compared to the non-pregnant women (d_{height} = 0.72, p = 0.045; d_{age} = 0.79, p = 0.03).

Table 1: Anthropometric data for the non-pregnant controls and the pregnant women at the early (EP) and late (LP) stage of pregnancy as well as postpartum (PP) (means ± standard deviation).

Groups	**Week**	**Age [year]**	**Body height [cm]**	**Body mass index [kg/m^2]**	**Thigh perimeter [cm]**
Controls	-	27.8 ± 4.1	166 ± 6	23.4 ± 2.7	53.0 ± 3.9
EP	16 ± 4 WoP	30.1 ± 4.3	170 ± 6 #	23.0 ± 2.9	51.5 ± 2.9
LP	29 ± 4 WoP	30.3 ± 4.3	-	25.1 ± 3.3 *	52.9 ± 2.9 *
PP	32 ± 9 after delivery	31.2 ± 4.2 †#	-	22.6 ± 4.0	50.5 ± 3.3

†significantly different to EP and LP (p < 0.05).

*significantly different to EP and PP (p < 0.05).

#significantly different to the controls (p < 0.05).

5.4.2 Muscle Strength

Knee extensor muscle strength, represented by the absolute knee joint moment, did not change during or after pregnancy (EP: 144.0 ± 34.8 Nm, LP: 146.9 ± 37.1 Nm, PP: 140.6 ± 33.9 Nm), while the relative knee joint moment, normalized to BM, was significantly smaller in the LP (2.07 ± 0.60 Nm/kg, d = 1.44, p = 0.029) compared to the EP (2.21 ± 0.60 Nm/kg) and PP (2.21 ± 0.60 Nm/kg). The postpartum absolute and relative knee extensor moments were not significantly different (p > 0.05) from the controls (Moment$_{abs}$ = 145.2 ± 31.8 Nm, Moment$_{rel}$ = 2.36 ± 0.55 Nm/kg).

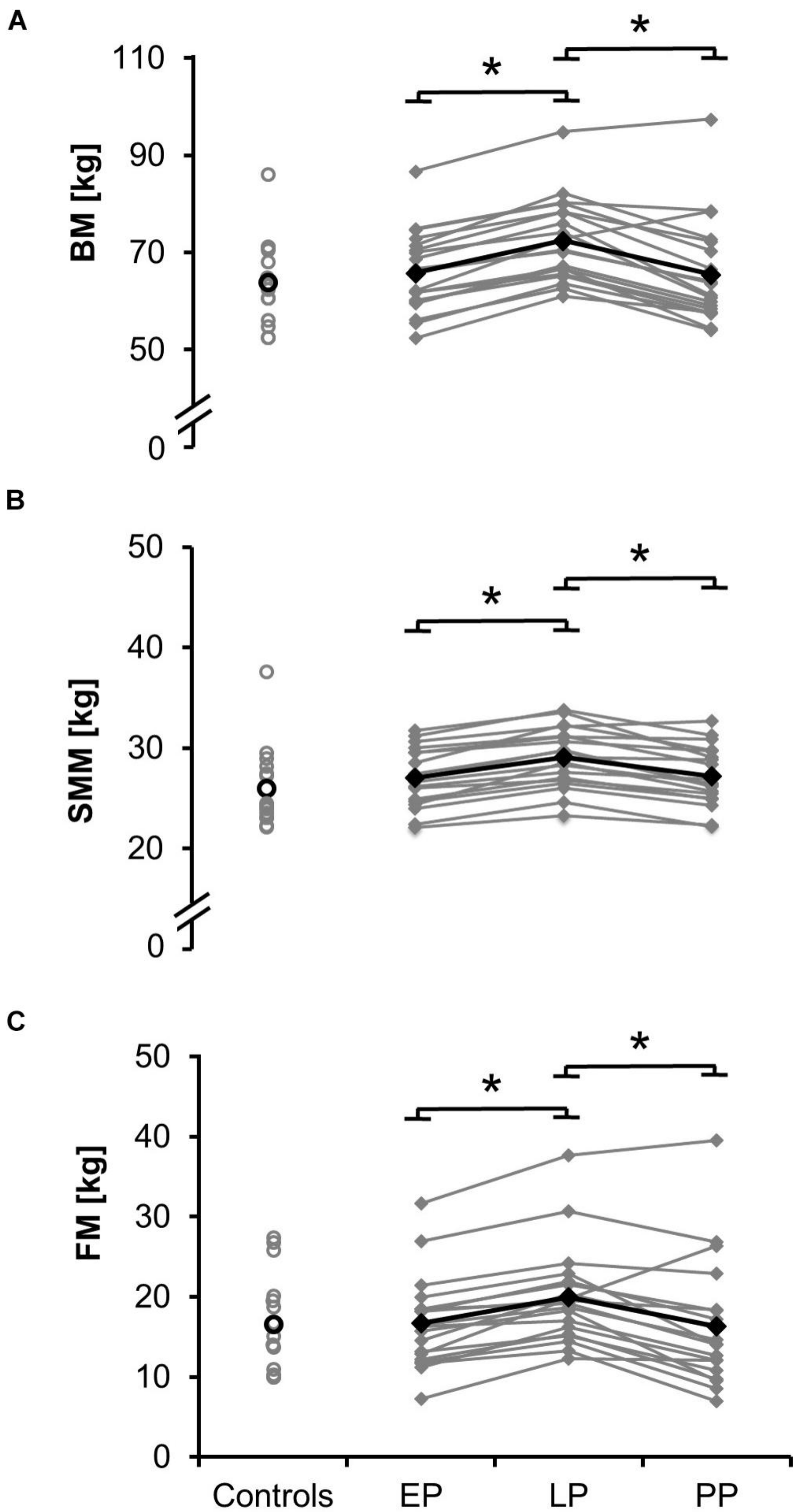

Figure 8: Means (black) and individual data (gray) for body mass BM (A), the skeletal muscle mass SMM (B), and fat mass FM (C) for the non-pregnant controls and the pregnant women at the early (EP) and late (LP) stage of pregnancy as well as postpartum (PP) ($^*p < 0.05$).

5.4.3 Vastus Lateralis Architecture

Muscle thickness and pennation angle significantly increased during pregnancy ($d_{thickness} = 2.19$, $p = 0.001$; $d_{angle} = 1.97$, $p = 0.002$) and significantly dropped postpartum ($d_{thickness} = 2.13$, $p = 0.001$; $d_{angle} = 1.47$, $p = 0.01$) (Figure 9B,C). FL remained constant during and after pregnancy (Figure 9A). The postpartum architectural parameters were not significantly different from the non-pregnant controls ($FL_{norm,PP} = 0.28 \pm 0.05$; $FL_{norm,Controls} = 0.32 \pm 0.07$, $p > 0.05$).

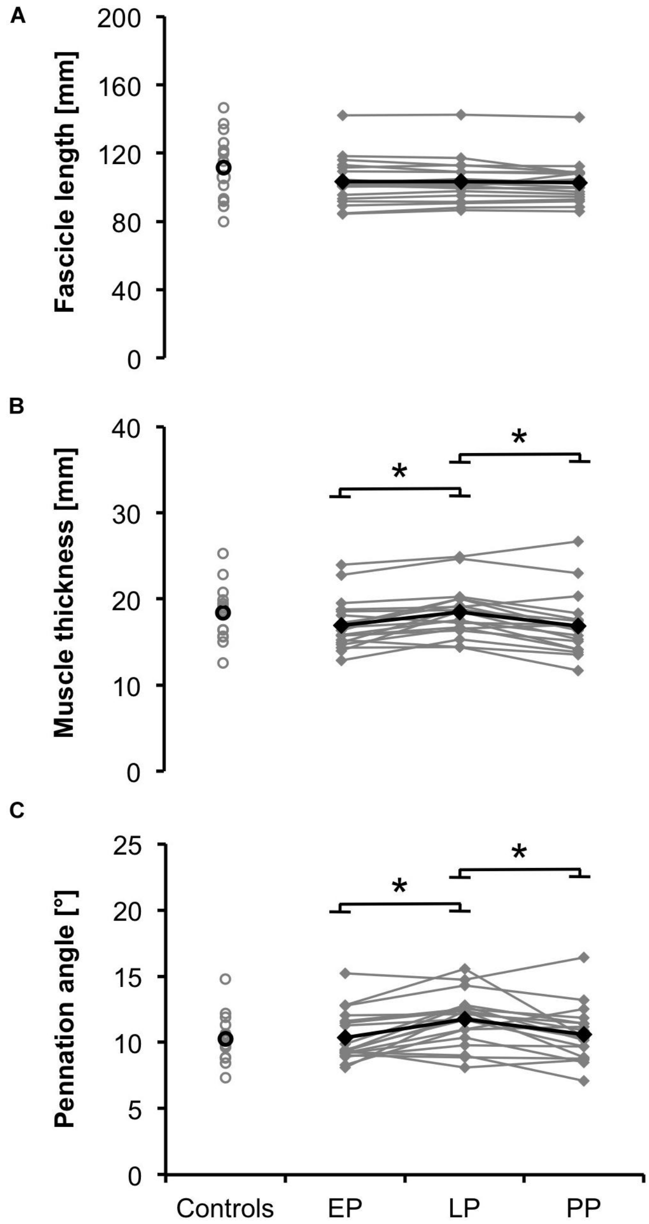

Figure 9: Means (black) and individual data (gray) for the architectural parameters fascicle length (A), muscle thickness (B), and pennation angle (C) for the non-pregnant controls and the pregnant women at the early (EP) and late (LP) stage of pregnancy as well as postpartum (PP) (*$p < 0.05$).

5.4.4 Body Composition

Total values for SMM (Figure 8B; relative proportion: EP: 41.0 ± 3.0 %, LP: 40.4 ± 3.2 %, PP: 42.2 ± 4.3 %), FM (Figure 8C; relative proportion: EP: 24.8 ± 6.0 %, LP: 27.2 ± 5.3 %, PP: 24.2 ± 7.4 %), TBW (absolute proportion: EP: 36.1 ± 3.5 l, LP: 38.5 ± 3.5 l, PP: 36.0 ± 3.6 l; relative proportion: EP: 54.8 ± 3.9 %, LP: 53.5 ± 4.2 %, PP: 55.9 ± 5.8 %), ICW and ECW (Figure 10A, B) significantly increased during pregnancy ($d_{SMM} = 0.70$, $p < 0.001$; $d_{FM} = 3.61$, $p < 0.001$; $d_{TBW} = 0.69$, $p < 0.001$; $d_{ICW} = 0.10$, $p < 0.001$; $d_{ECW} = 0.64$, $p < 0.001$) while they significantly dropped postpartum ($d_{SMM} = 0.62$, $p < 0.001$; $d_{FM} = 1.87$, $p = 0.003$; $d_{TBW} = 0.70$, $p < 0.001$; $d_{ICW} = 0.64$, $p < 0.001$; $d_{ECW} = 0.79$, $p < 0.001$). Body composition (relative proportion: SMM: 40.8 ± 4.4 %, FM: 25.6 ± 7.4 %, TBW: 54.5 ± 5.5 %) of the non-pregnant controls did not differ from the postpartum measurements.

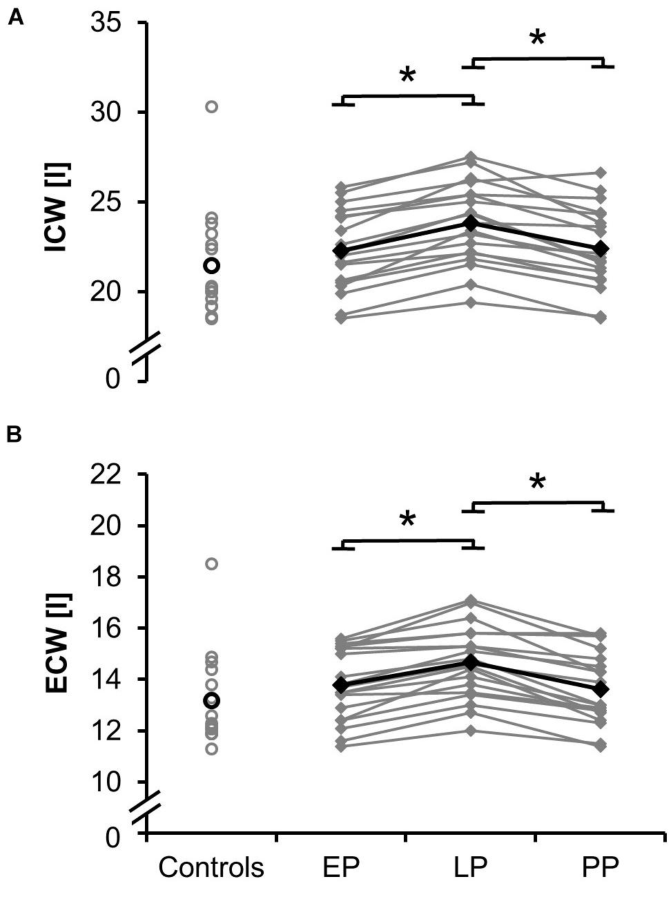

Figure 10: Means (black) and individual data (gray) for the intracellular water ICW (A) and extracellular water ECW (B) for the non-pregnant controls and the pregnant women at the early (EP) and late (LP) stage of pregnancy as well as postpartum (PP) (*$p < 0.05$).

5.4.5 Relationships Between Muscle Architecture, Body Mass and Water Content

Changes in the pennation angle from the LP to PP correlated moderately with changes in BM (Figure 11A). The larger the decrease of BM between the LP and PP the larger the decrease in the pennation angle. Changes in BM during pregnancy (between the LP and EP) did not correlate with changes in pennation angle. No significant correlations were found for the relationships between the changes in the BM and the changes in muscle thickness (Figure 11C) as well as between the changes in the TBW and changes in the pennation angle (Figure 11B) or muscle thickness (Figure 11D).

Changes in SMM from the EP to LP and the LP to PP correlated significantly with changes in the ICW and ECW (EP $\rightarrow$ LP: ICW: $r = 0.920$, $p < 0.001$; ECW: $r = 0.823$, $p < 0.001$; LP $\rightarrow$ PP: ICW: $r = 0.962$, $p < 0.001$; ECW: $r = 0.831$, $p < 0.001$).

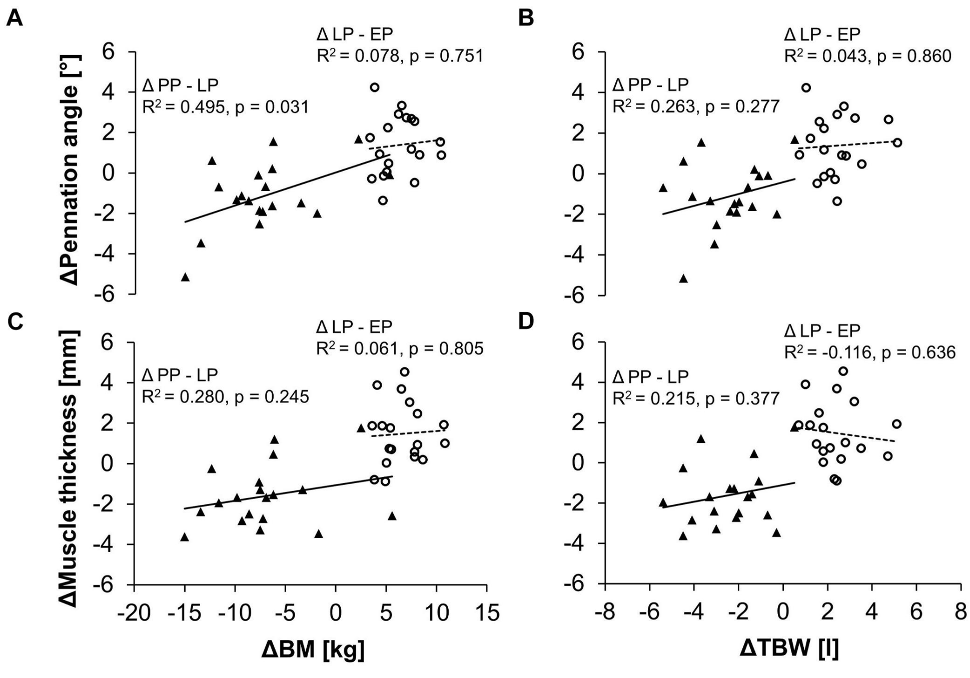

Figure 11: Relationship between the changes in body mass (BM) and the changes in the pennation angle (A) or muscle thickness (C) as well as between the changes in the total body water (TBW) and the changes in the pennation angle (B) or muscle thickness (D) in the pregnant women. Demonstrated are the differences of the parameters between the early and late stage of pregnancy (Δ LP-EP, circles) as well as between the postpartum period and the late stage of pregnancy (Δ PP-LP, triangles) and the respective linear regression lines (dashed line for Δ LP-EP, solid line for Δ PP-LP).

5.4.6 Individual Data Sets

In addition to the measurement time-points EP, LP, and PP we were able to measure two women additionally 37 and 36 weeks prior pregnancy (Table 2). Similar to the group mean values, pennation angle, muscle thickness, body content, and water distribution parameters increased in the LP while the absolute knee joint moment remained constant. After delivery the body content and water distribution returned to the prior pregnancy levels.

Table 2: Changes in the vastus lateralis muscle architecture, body composition, and water distribution for two women (Women-A: age 34 years, height 169 cm; Women-B: age 26 years, height 162 cm) for the four measurement time-points prior pregnancy, in the early (EP) and late (LP) stage of pregnancy as well as postpartum (PP).

Session	Week	Knee extensor moment[Nm]	Fascicle length [mm]	Muscle thickness [mm]	Pennation angle [°]	BM [kg]	SMM [kg]	FM [kg]	ICW [l]	ECW [l]
Woman-A										
prior	37 pre	144.7	79.6	12.6	10.5	56.2	22.3	15.1	18.6	11.3
EP	12 WoP	159.2	84.4	12.8	9.4	55.5	22.1	14.5	18.5	11.4
LP	28 WoP	162.0	86.4	15.3	11.9	63.6	23.3	20.4	19.4	12.0
PP	31 post	156.8	85.8	13.8	10.3	57.4	22.3	16.1	18.6	11.5
Woman-B										
prior	36 pre	175.5	92.6	12.9	12.2	54.8	24.5	10.1	20.3	12.3
EP	14 WoP	162.3	95.3	18.5	11.5	52.4	24.9	7.3	20.6	12.4
LP	27 WoP	164.5	97.7	18.7	12.4	61.0	27.0	12.3	22.2	13.4
PP	25 post	147.1	95.7	17.5	10.9	57.7	24.9	12.1	20.6	12.8

5.5 Discussion

This longitudinal study investigated the effect of pregnancy on muscle properties of the lower extremities measured in the EP and LP as well as six months after delivery. While knee extensor muscle strength remained constant during and after pregnancy we found an increase in muscle thickness and pennation angle of the vastus lateralis in the LP returning to non-pregnant levels in the PP. Thus, regarding knee extensor muscle thickness and pennation angle our first hypothesis is confirmed, while regarding muscle strength we have to dismiss our hypothesis. Alterations in muscle properties were neither directly associated with changes in the BM nor with changes in the body composition. Thus, our second hypothesis had to be rejected.

The pregnancy-induced change in muscle architecture may be attributed to a combination of changes in the endocrine system, BM, and body composition. As there are no comparable studies investigating the effect of those factors on architectural properties of peripheral skeletal muscles in pregnant women three probable factors influencing the structure of the muscle are discussed separately: (1) loading, (2) water content, and (3) hormone levels during pregnancy.

An increase in muscle thickness and pennation angle is usually related to the formation of new sarcomeres in parallel (Reeves et al., 2006). This protein based alteration in the muscle structure is known as an adaptive response to overload, for example, through exercise (Aagaard et al., 2001), or to an increased functional demand, for example, through a surgical removal of a synergistic muscle (Johnson and Klueber, 1991). Also increases in BM have been observed to trigger alterations in the quadriceps femoris muscle with an increase in the anatomical cross-sectional area (Delmonico et al., 2009). We may argue that the 10 % increase in BM (6.6 ± 2.1 kg, range: 3.6 - 10.8 kg) from the 16^{th} - 29^{th} WoP may have promoted hypertrophy of the vastus lateralis muscle, thereby increasing the SMM and the thigh perimeter. However, we may question that weight gain during pregnancy is the single factor contributing to alterations in muscle architecture which is somehow in agreement with our results demonstrating that neither the changes in muscle thickness nor the changes in pennation angle from the EP to LP significantly correlated with the changes in BM. It is also conceivable that the increase in muscle thickness may have been influenced at least partly by changes in water content during pregnancy, since we detected a significant increase of the ICW and ECW in the LP.

A progressive increase in the water content during pregnancy has been reported by numerous studies (Lukaski et al., 1994; Valensise et al., 2000; Larciprete et al., 2003) and has been suggested to be fundamental for the expansion of the plasma volume, facilitating the increase in the mother's cardiac output (Lukaski et al., 1994; Valensise et al., 2000; Larciprete et al., 2003; Cho et al., 2011). After delivery, plasma volume returns to the non-pregnant levels (Hytten and Paintin, 1963), and the water content decreases again (Lukaski et al., 1994; Cho et al., 2011). This reduction in the water content can also be observed in our postpartum data. Since edema in the lower limbs are known to increase the circumference of the leg (Berard et al., 2002), it seems conclusive that water retention during pregnancy may have partly contributed to the 1.9 cm increase in the thigh perimeter in the LP. However, the increased perimeter cannot solely be attributed to edema as this mainly occurs in the extracellular space. The increase in the ICW content could also have led to a thickening of the muscle fibers which could have resulted in a measureable thickening of the muscle tissue. However, it seems that water retention within the muscles does not affect muscle architecture since body water and muscle thickness were not related to each other. We need to point out that we were not able to subtract the content of amniotic fluid from the TBW, which may have affected our results.

Hormonal changes during pregnancy could also have affected muscle architecture. The endocrine system is known to modulate anabolic processes in muscles and to affect muscle plasticity (Hackney, 1999; Hansen and Kjaer, 2014). While increased estrogen levels during pregnancy have been associated with uterus muscle growth (Rundgren, 1974), the anabolic effect of estrogen on peripheral skeletal muscles is still debated (Hansen et al., 2003). However, as observed in the hind limbs in mice gestation seems to improve the regeneration processes in skeletal muscles and to counteract negative effects of aging (Falick Michaeli et al., 2015). This improvement in regenerative capabilities during pregnancy may hint toward favorable metabolic conditions promoting the adaptation to training and mechanical loading.

While our results clearly indicate, that pregnancy leads to changes in muscle architecture, and that this change is not caused by a single factor, it remains to be established which pregnancy-associated combination of factors contributes to this change. Furthermore, it needs to be established how this change in muscle architecture affects muscle function.

Despite increases in muscle thickness we did not observe any increase in the knee extensor muscle strength. To our knowledge, no study has yet investigated lower limb muscles during pregnancy. A study on upper limb muscles has observed a 9 % decline in handgrip strength in the LP compared to the middle stage of pregnancy (Atay and Basalan Iz, 2015). It is possible that both the upper and lower body are subjected to different adaptation processes during pregnancy. Regional differences in muscle adaptation have previously been observed in other scenarios (Bemben et al., 1991; Janssen et al., 2000). As requirements regarding balance maintenance and stabilization of the heavier body during standing and locomotion are enhanced during pregnancy, a reduction in lower body strength seems unreasonable from an evolutionary perspective. Changes in the vastus lateralis muscle architecture may point toward an adaptive response to meet the increased demands. However, absolute muscle strength did not increase. Muscle strength relative to BM even dropped in the LP. As consequence, it seems likely that in the event of balance perturbations muscle strength may not be sufficiently high enough to prevent the fall of a heavier body.

The dimension of force production in the LP may also be affected by changes in the women's fitness level during pregnancy. Atay and Basalan Iz (2015) state that the loss in upper limb muscle strength in pregnant women is primarily attributed to a reduction in physical activity. However, even if our participants may have progressively reduced the intensity of their activities during pregnancy this did at least not lead to a loss in the knee extensor muscle strength. Further, psychological factors may have affected force production in the LP. Primarily in the 29^{th} WoP, when the fetus is getting close to its birth length, our participants may not have felt confident to produce the maximum isometric force on the dynamometer. In addition, elevated anxiety levels may have influenced the women's performance during the ramp contraction trials. As the prevalence of self-reported anxiety has been reported to continuously increase during pregnancy from 18 % in T1 to 25 % in T3, while decreasing in the PP (Dennis et al., 2017; Nakic Rados et al., 2018), the women may have unconsciously changed their behavior in the LP.

5.6 Conclusion

In conclusion, there is no evidence that lower limb muscle strength decreases during pregnancy. In contrast, we established a pregnancy-induced change in the muscle architecture of the lower limb muscles which is likely to be caused by multiple factors such as changes in the endocrine system, BM, and body composition. However, the risk of injury may be increased during pregnancy since muscle strength relative to BM dropped in the LP while the physical demand increases due to the increased BM. Thus, strength exercises of the peripheral skeletal muscles and physical activity may benefit health during pregnancy.

5.7 Ethics Statement

This study was carried out in accordance with the recommendations of the "Ethics Committee Charité - Universitätsmedizin Berlin" with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol (No.: EA2/130/15) was approved by the "Ethics Committee Charité - Universitätsmedizin Berlin".

5.8 Author Contributions

KL conceived the design of the study. MB carried out the measurements and data analysis and drafted the manuscript. RM participated in the data collection and developed the data analysis algorithm. LH attended the measurements and was responsible for potential medical issues. KL and AA made important contributions during preparation and revision. All authors gave final approval for publication and agreed to be responsible for the content of the article.

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6 Second article | Patellar Tendon Stiffness is not reduced during Pregnancy

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6.1 Abstract

It is believed that hormonal changes during pregnancy lead to an increased compliance in ligaments and tendons, increasing the risk to suffer from connective tissue injuries particularly during exercise. While the laxity of the pelvic ligaments may increase to facilitate childbirth, to our knowledge no study has ever investigated the mechanical properties of human tendons in different stages of pregnancy. Thus, the purpose of our longitudinal study was to investigate the mechanical properties of the patellar tendon in different stages of pregnancy and postpartum.

Nineteen pregnant women (30 ± 4 years) and eleven non-pregnant controls (28 ± 3 years) performed maximum isometric knee extension contractions on a dynamometer. Muscle strength and mechanical properties of the patellar tendon were determined integrating ultrasound, kinematic, and EMG measurements. In pregnant women, measurements were performed in the 16 ± 4^{th} WoP (EP), the 29 ± 4^{th} WoP (LP) and 32 ± 9^{th} weeks postpartum (PP).

On average, muscle strength as well as patellar tendon stiffness, force, and relative strain did not change during pregnancy and did not differ from non-pregnant controls. Tendon length measured at 90° knee flexion continuously increased during and after pregnancy (tendon length PP > EP; PP > controls).

Our results indicate that patellar tendon stiffness is not universally affected by pregnancy. We found no evidence to support the often-stated assumption that tendons would become more compliant during pregnancy. However, variability between individuals as well as the progressive increase in tendon rest length during and after pregnancy and its implications on injury risk need to be further examined.

Keywords:
tendon, stiffness, length, muscle strength, exercise, laxity, injury, pregnancy

6.2 Introduction

It is well established that physical activity during pregnancy has beneficial effects on maternal and fetal health (Vladutiu et al., 2010) decreasing the risk of pregnancy associated disorders such as preeclampsia or gestational diabetes (DeMaio and Magann, 2009). Whilst pregnant women are encouraged to pursue low-impact activities such as aerobic training or walking to maintain their cardiovascular fitness (DeMaio and Magann, 2009; Nascimento et al., 2012), it has been recommended to avoid high-intensity exercise (DeMaio and Magann, 2009). During excessive physical activity pregnant women are thought to be prone to overheating (Sasaki et al., 1995), since their core temperature has been reported to increase with the growing fetus (Buxton and Atkinson, 1948). In addition, strenuous exercise may reduce blood flow to the placenta, which may impair fetal development (Rauramo and Forss, 1988). In order to maintain overall body strength and to improve body posture or reduce back pain during pregnancy (Zavorsky and Longo, 2011) strength training with low weights and low intensity has been suggested.

However, even when moderate exercise is undertaken, pregnant women are often cautioned that hormonal changes during pregnancy may increase ligament and tendon compliance (Östgaard et al., 1993; Dumas and Reid, 1997; Ritchie, 2003) possibly leading to connective tissue injuries and joint pain, such as patellofemoral dysfunction (Ritchie, 2003; Harland et al., 2014). Increased connective tissue compliance is further believed to cause joint instability (Ritchie, 2003) which may impair postural stability. Indeed, recent studies demonstrated an increase in postural sway (Jang et al., 2008; Oliveira et al., 2009) as well as impairments in dynamic (Inanir et al., 2014) and static postural stability, already occurring in the EP (Bey et al., 2018). Since impairments in postural stability are associated with the high incidence of falls in pregnant women (Dunning et al., 2010) this may, in turn, lead to further injuries.

It has been known for decades and has been well documented that the compliance of the pubic ligaments increases during pregnancy which is an essential process to facilitate childbirth (Young, 1940). Recent studies suggest that the laxity of the peripheral joints might similarly increase during pregnancy, with a greater range of motion in the knee joint (Schauberger et al., 1996), the elbow (Schauberger et al., 1996), the wrist (Marnach et al., 2003), and the metacarpophalangeal joints (Calguneri et al., 1982; Schauberger et al., 1996) being reported. While those studies in humans were drawing conclusions on connective tissue properties from range of motion changes, not directly measuring tissue properties, one study in pregnant rabbits has actually determined the stiffness of the medial collateral ligament by in vitro material testing (Hart et al., 2000). This study did not find any effect of pregnancy on structural, material and viscoelastic properties of the rabbit's medial collateral ligament.

To our knowledge, in pregnant women the mechanical properties of tendons and ligaments in peripheral joints have never been investigated. However, hormonal changes occurring during pregnancy may affect connective tissue properties even in peripheral regions of the human body, thereby possibly increasing the risk of injury. Hormonal fluctuations during the menstrual cycle such as increased hRLX levels have already been reported to be associated with a decreased patellar tendon stiffness (Pearson et al., 2011). As hRLX levels are also elevated in pregnant women, being ten times larger compared to levels occurring in non-pregnant women (MacLennan et al., 1986a), the hormonal effect on the patellar tendon is expected to be potentiated during pregnancy. However, hormonal effects on tendons are likely to be tendon-specific since levels of hRLX during the menstrual cycle were not related to the gastrocnemius tendon stiffness (Pearson et al., 2011).

The aim of our longitudinal study was to investigate the mechanical properties of the patellar tendon at two different stages of pregnancy and six months after delivery. In addition, the postpartum values were compared to non-pregnant controls.
We hypothesized that patellar tendon stiffness decreases during pregnancy. Quantifying the effect of pregnancy on the mechanical properties of tendons may help to better assess injury risk and to derive from that appropriate recommendations regarding physical activity during pregnancy. Further, our study may contribute to a better understanding of hormonal effects on female connective tissue properties in general, as also in other contexts hormonal variations are discussed to affect injury risk (e.g., association of anterior cruciate ligament rupture incidence with certain phases of the menstrual cycle) (Herzberg et al., 2017).

6.3 Materials and Methods

6.3.1 Participants

Twenty-one pregnant and eleven non-pregnant healthy non-sedentary women agreed to participate in this study. Two pregnant women dropped out of the study due to medical issues in the LP. Therefore, 19 pregnant and eleven non-pregnant controls completed the study. Previous studies have shown that this sample size is sufficient to detect hormone related or training induced changes in patellar tendon stiffness (Pearson et al., 2011; Mersmann et al., 2016). In twelve menstruating women, Pearson et al. (2011) found a significant correlation ($r = -0.560$, $p < 0.001$) between hRLX hormone levels and patellar tendon stiffness. Another study with twelve participants detected a 4 % increase in patellar tendon stiffness ($p = 0.003$) after a twelve months of sport-specific training (Mersmann et al., 2016).

In the pregnant women patellar tendon properties and the maximum knee joint moment were determined in the EP (16 ± 4^{th} WoP), LP (29 ± 4^{th} WoP) and at least six months postpartum (PP, 32 ± 9 weeks). Except for two participants (Table 5) a measurement prior to pregnancy was not possible. Thus, the time-point for the postpartum measurement was chosen to reflect the non-pregnant status assuming that six months after delivery the women would have recovered from childbirth and hormone levels would have returned to pre-pregnancy levels. A study by Schauberger et al. (1996) has demonstrated that increased levels of hRLX during pregnancy returned to pre-pregnancy levels within two weeks postpartum.

In the non-pregnant controls the same variables were determined once. Women with a multiple pregnancy, severe pathological pregnancy-associated symptoms and present or past injuries of the knee were excluded from the study. Pregnant women (30 ± 4 years) were on average 2 years older than the non-pregnant controls (28 ± 3 years). This study was carried out in accordance with the recommendations of the local ethics committee Charité - Universitätsmedizin Berlin with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by the ethics committee Charité - Universitätsmedizin Berlin.

6.3.2 Experimental Setup

Briefly, the women performed five slow maximal isometric ramp contractions and two submaximal isometric knee flexion contractions on a dynamometer. Length changes of the patellar tendon were recorded with ultrasound. Muscle strength of the knee extensors was assessed by the knee joint moment measured by the dynamometer. To take gravitational forces and a misalignment of the knee joint and the dynamometer axis during the contractions into account (Arampatzis et al., 2004) a motion capture system was used. To subtract the contribution of the antagonistic moment from the measured knee joint moment the antagonist muscle activity was measured using EMG measurements (Mademli et al., 2004). All measurements were conducted with the dominant leg, defined as the commonly-used leg for kicking a ball. For a schematic representation of the experimental setup see Figure 12.

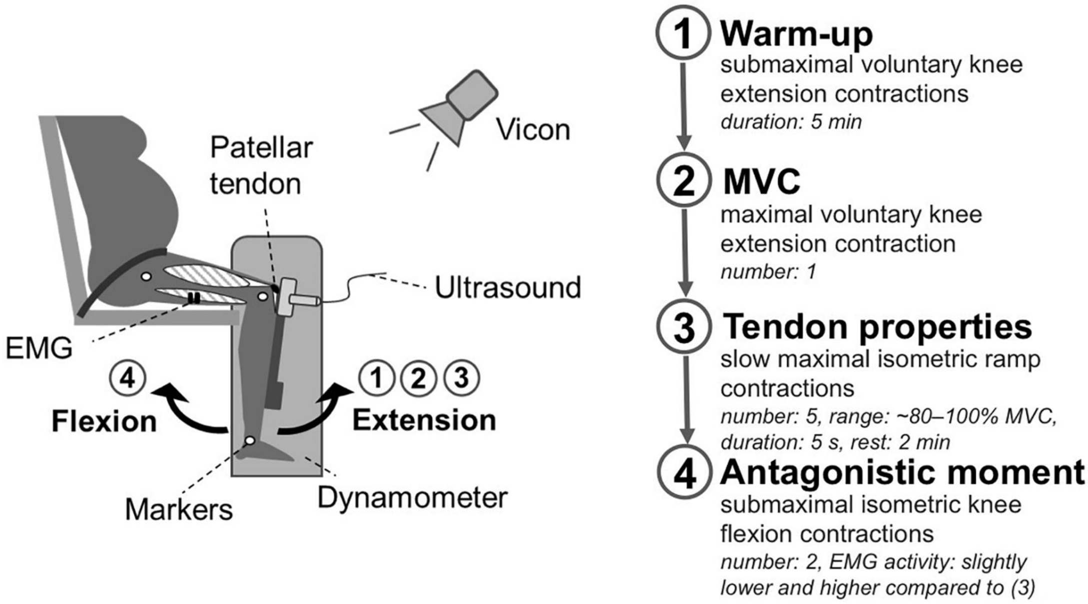

Figure 12: Schematic representation of the experimental setup. Participants were seated on a dynamometer with a 90 ° knee joint angle. In this position, the participants performed a 5 min warm-up with submaximal voluntary knee extension contractions (1). Thereafter, the women performed a maximal voluntary knee extension contraction to estimate the maximal voluntary moment (2). To determine tendon properties (3) the knee joint moment was assessed during five slow maximal isometric ramp contractions ($\sim 80 - 100\,\%$ MVC), considering EMG activity of the antagonists and movements of the knee joint relative to the dynamometer captured by Vicon. The tendon elongation was recorded using ultrasound. Subsequently, two submaximal isometric knee flexion contractions (4) were performed to estimate the antagonistic contribution to the measured knee joint moment during the ramp contractions.

6.3.2.1 Measurement of Maximum Knee Joint Moment

Participants were seated on a dynamometer (Biodex Medical System 3, Shirley, NY, United States) with a 90 ° resting knee joint angle (Pearson et al., 2011; Hansen et al., 2013) and an 85 ° trunk angle. To prevent hip movements the participants were fastened to the seat using a non-elastic strap. After a 5 min warm-up phase with submaximal voluntary knee extension contractions the women performed one maximal voluntary knee extension contraction (MVC) as well as five slow maximal isometric ramp contractions ($\sim 80-100\,\%$ MVC) with a steadily increasing effort to the maximum within 5 s, and 2 min rest between contractions.

To take gravitational forces and a misalignment of the knee joint and the dynamometer axis during contraction into account (Arampatzis et al., 2004), kinematic data were collected using a Vicon motion capture system (version 1.7.1; Vicon Motion Systems, Oxford, United Kingdom) integrating seven cameras at a frame rate of 250 Hz. Five reflective markers were captured which were positioned at the trochanter major, lateral, and medial epicondyle of the femur as well as the lateral and medial malleolus.

To determine the resultant knee extensor moment without the antagonistic contribution of the knee flexors during the ramp contractions, the antagonistic moment was subtracted from the measured knee joint moment. The antagonistic moment was estimated by establishing the relationship of the EMG activity of the knee flexors during the ramp contractions and the exerted moment of the knee flexors during knee flexion contractions, when acting as agonists (Mademli et al., 2004). The EMG activity of the flexors was recorded with one pair of bipolar surface electrodes (Myon m320RX; Myon, Baar, Switzerland) which were placed centrally over the long head of the biceps femoris in the direction of the muscle fibers. The sample rate was set at 1000 Hz. The exerted moment was measured during two submaximal isometric knee flexion contractions with an intensity resulting in a slightly lower and higher activity than the previously determined activity during the ramp contractions (Mademli et al., 2004).

6.3.2.2 Measurement of Mechanical Tendon Properties

Patellar tendon elongation during the knee extension contractions was analyzed in the sagittal plane using a 10 cm ultrasound probe (7.5 MHz, My Lab60, Esaote, Genova, Italy). Ultrasound images were captured at 25 Hz. Externally induced trigger signals set in the beginning and the end of the ramp contractions facilitated the synchronization of the ultrasound images and the kinematic data.

Using a custom written Matlab interface (version R2012a; MathWorks, Natick, MA, United States), the patellar tendon elongation was analyzed frame by frame manually tracking the deep insertion of the tendon at the patellar apex and the tibial tuberosity (Mersmann et al., 2014). Tendon rest length at 90 ° knee joint angle was defined as tendon length in the inactive state of the muscles being determined by tracing the deep boundary of the tendon Figure 13. In a 90 ° knee flexion position the patellar tendon may have been subjected to a small pretension, thus tendon length in a 90 ° knee flexion position may differ from the true rest length. To examine the variation of the rest lengths within each stage of pregnancy we calculated the standard deviation of the rest lengths for each participant separately and determined from the results the overall mean and standard deviation. The within-day variation was 0.77±0.66 mm for EP, 0.71±0.51 mm for LP, and 0.77±0.38 mm for PP. Tendon elongation was measured in the active state of the muscles when the rest length was exceeded.

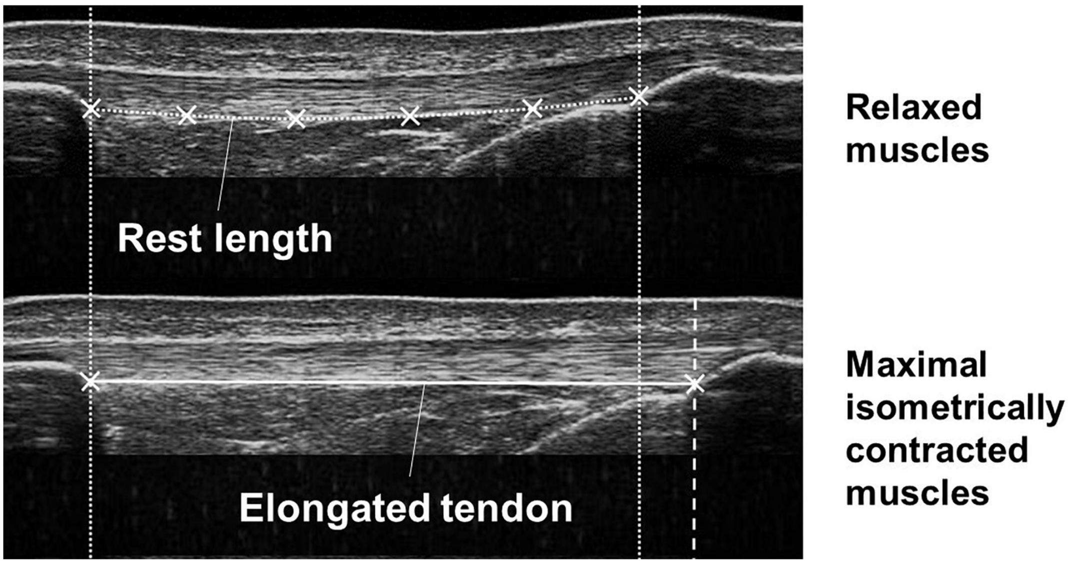

Figure 13: Ultrasound images demonstrating the tendon in the relaxed (upper image) and maximal isometrically contracted state (lower image) of the muscles. Tendon rest length and tendon elongation were measured defining reference points at the patellar apex and the tibial tuberosity and the deep boundary of the tendon.

To determine the tendon relative strain, the maximum elongation was normalized to the tendon rest length. Tendon force was calculated dividing the previously measured knee extension moment by the tendon moment arm, which was predicted based on the body height and the BM from the PP measurement (Mersmann et al., 2016). After calculating the average of five tendon force-elongation ratios (Schulze et al., 2012), the resultant force-elongation curve was fitted using a second-order polynomial. Examples for force-elongation ratios during pregnancy are presented in Figure 14. Tendon stiffness was defined as the slope of a regression line between 50 % and 100 % of the maximum tendon force. Toe limit elongation was obtained as abscissa of the intersection point of the regression line and the zero force axis (Seynnes et al., 2013).

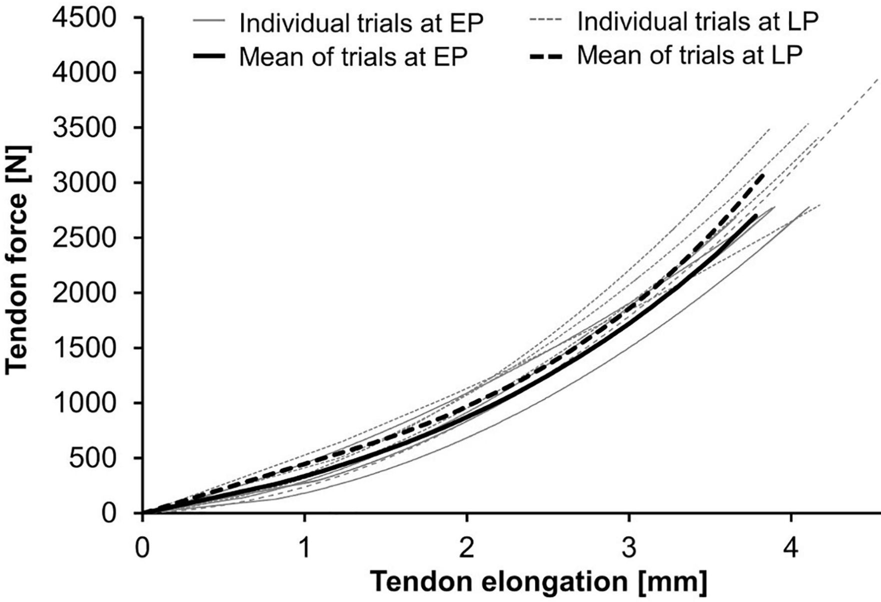

Figure 14: Tendon force-elongation ratios at the early (EP) and late (LP) stage of pregnancy. Demonstrated are the individual trials and their means in one pregnant woman (for data see Woman-A in Table 5)

6.3.3 Statistical Analysis

Statistical analysis was performed using IBM SPSS Statistics (Version 21, 32 Bit, IBM, United States). Normality of the standardized residuals was analyzed conducting the Shapiro-Wilk test. Differences between the EP, LP, and PP were investigated using a one-way repeated measures ANOVA considering the assumption of sphericity. If the assumption of sphericity was violated the Greenhouse-Geisser correction was used. For post hoc comparisons paired t-tests with Bonferroni adjustment were performed. If the data were not normally distributed the Friedman's test and the Wilcoxon signed-rank test for pairwise comparisons were conducted.

To compare the anthropometric measures (body height, moment arm, and age) and the postpartum session of the pregnant women with the non-pregnant controls either an independent samples t-test or the Mann-Whitney U-test for not normally distributed data were used. The effect size was calculated using Cohen's d for normally distributed data. For not normally distributed data the effect size r was determined dividing the z-scores of the Wilcoxon or Mann-Whitney U-test by the square root of the number of total observations. Subsequently, the result r was converted into d. The alpha level for all statistical tests was set at $\alpha = 0.05$.

6.4 Results

6.4.1 Anthropometric Measures

BM and BMI in the LP were significantly higher compared to the EP ($d_{mass} = 3.29$, $p < 0.001$; $d_{BMI} = 3.65$, $p < 0.001$) and PP ($d_{mass} = 2.88$, $p < 0.001$; $d_{BMI} = 2.88$, $p < 0.001$) (Table 3). BM and BMI in the PP did not differ from non-pregnant controls. Body height (Table 3) and moment arm (Table 4) were significantly larger in the pregnant women compared to the non-pregnant controls ($d_{height} = 0.99$, $p = 0.014$; $d_{momentarm} = 1.03$, $p = 0.011$).

Table 3: Anthropometric data for the pregnant women in the early (EP) and late (LP) stage of pregnancy, postpartum (PP), and for the non-pregnant controls (means ± standard deviation)

Groups	**Week**	**Body mass [kg]**	**Body height [cm]**	**Body mass index [kg/m^2]**
Controls	-	60.3 ± 5.5	165 ± 4	22.3 ± 2.2
EP	16 ± 4 WoP	66.2 ± 7.8	170 ± 6 #	23.0 ± 2.9
LP	29 ± 4 WoP	72.3 ± 8.4 *	-	25.1 ± 3.3 *
PP	32 ± 9 after delivery	65.2 ± 10.8	-	22.6 ± 4.0

*significantly different to EP and PP ($p < 0.05$).

#significantly different to the controls ($p < 0.05$).

6.4.2 Patellar Tendon Properties

Tendon stiffness (EP: 1,060 ± 195 N/mm, LP: 1,033 ± 238 N/mm, PP: 1,064 ± 220 N/mm) (Figure 15A) did not change during and after pregnancy. Similarly, for the knee extensor moment (Table 4), tendon relative strain (EP: 7.3 ± 1.4 %, LP: 7.3 ± 1.3 %, PP: 7.5 ± 1.6 %) and maximum tendon force (EP: 2,832 ± 674 N, LP: 2,899 ± 700 N, PP: 2,781 ± 661 N) (Figure 15B,C) no significant differences were detected. Tendon rest length (Figure 15D) increased during and after pregnancy (EP: 48.2 ± 3.3 mm, LP: 49.3 ± 3.8 mm, PP: 50.6 ± 3.4 mm) being significantly larger in the PP compared to the EP ($d = 0.732$, $p = 0.002$). Maximum elongation and toe limit elongation (Table 4) did not change during and after pregnancy.

Postpartum rest length (Figure 15D) significantly increased compared to the non-pregnant controls (rest length = 47.1 ± 4.9 mm; $d = 0.88$, $p = 0.028$). For the toe limit elongation (Table 4) a tendency toward a difference from the controls ($d = 0.71$, $p = 0.0501$) was detected. The postpartum tendon stiffness (stiffness = 1,147 ± 321 N/mm), knee extensor moment, tendon moment arm, and maximum elongation (Table 4) were not significantly different between pregnant women and controls.

Table 4: Knee extensor moment and patellar tendon properties for the pregnant women in the early (EP) and late (LP) stage of pregnancy, postpartum (PP), and for the non-pregnant controls (means ± standard deviation).

Groups	Knee extensor moment [Nm]	Moment arm [mm]	Toe limit elongation [mm]	Maximum elongation [mm]
Controls	144.5 ± 34.1	49.4 ± 0.7	0.92 ± 0.38	3.34 ± 0.73
EP	144.0 ± 34.8	-	1.00 ± 0.39	3.54 ± 0.70
LP	146.9 ± 37.1	-	1.02 ± 0.57	3.61 ± 0.82
PP	140.6 ± 33.9	50.5 ± 1.2 #	1.29 ± 0.57 °	3.79 ± 0.86

#significantly different to the controls ($p < 0.05$).

°tendency toward a difference from the controls ($p = 0.0501$).

6.4.3 Individual Data Sets

In two women we were able to obtain data at 37 and 36 weeks prior pregnancy in addition to the EP, LP, and PP time-points (Table 5). While it is not possible to statistically analyze those individual two data sets, the data are in agreement with the comparison

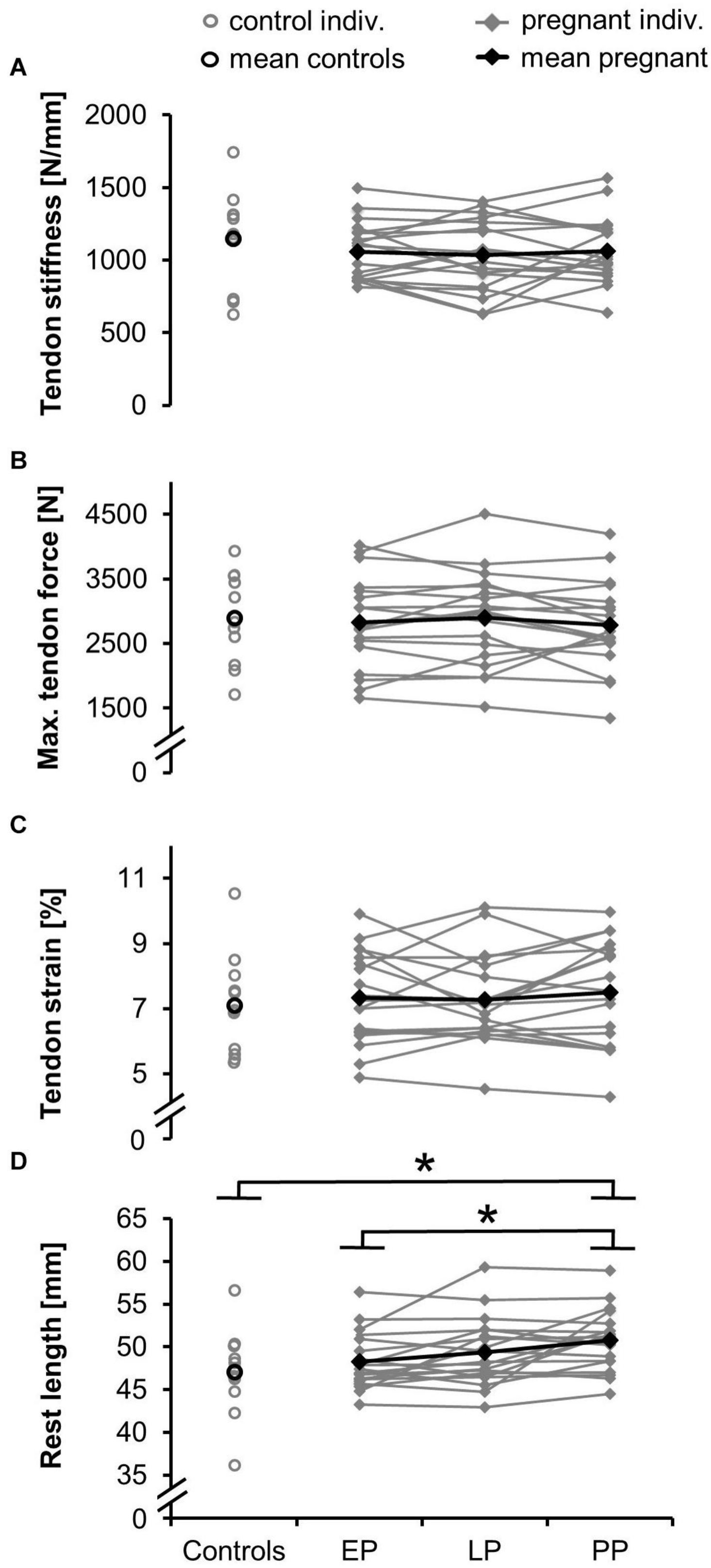

Figure 15: Means and individual data for the tendon stiffness (A), maximum tendon force (B), relative strain (C), and rest length (D) in the pregnant women in the early (EP) and late (LP) stage of pregnancy, postpartum (PP) and in the non-pregnant controls (*significantly different, $p < 0.05$).

of PP with non-pregnant controls. Both women show no reduction in tendon stiffness during pregnancy. While the tendon stiffness in Woman-A increased during pregnancy up to + 17 %, marginal changes up to + 4 % were found in Woman-B. In both women, rest length at a 90 ° knee joint angle was observed to increase during and after pregnancy (Woman-A: + 16 %, Woman-B: + 6 %).

Table 5: Changes in the body mass, knee extensor moment and patellar tendon properties for two women (Women-A: age 34 years, height 169 cm; Women-B: age 26 years, height 162 cm), who have been measured prior pregnancy, in the early (EP) and late (LP) stage of pregnancy as well as postpartum (PP).

Session	Week	Body mass [kg]	Knee extensor moment [Nm]	Rest length [mm]	Toe limit elongation [mm]	Maximum elongation [mm]	Relative strain [%]	Tendon force [N]	Stiffness [N/mm]
Woman-A									
prior	37 pre	56.2	144.7	46.3	0.93	3.22	6.96	2,842	1,183
EP	12 WoP	55.5	159.2	53.2	1.39	3.72	7.00	2,729	1,117
LP	28 WoP	63.6	162.0	53.6	1.59	3.84	7.19	3,282	1,382
PP	31 post	57.4	156.8	52.8	1.93	4.53	8.59	3,150	1,193
Woman-B									
prior	36 pre	54.8	175.5	48.7	1.11	3.68	7.56	3,573	1,312
EP	14 WoP	57.7	162.3	48.6	0.56	2.85	5.87	3,365	1,358
LP	27 WoP	61.0	164.5	46.3	0.45	2.93	6.31	3,391	1,332
PP	25 post	52.4	147.1	51.5	0.92	3.32	6.45	3,026	1,216

6.5 Discussion

This is the first study providing evidence on the mechanical properties of human tendons in different stages of pregnancy. Our study did not detect changes in patellar tendon mechanical properties during pregnancy. Therefore, we reject our hypothesis and conclude that tendon stiffness does not universally decrease during pregnancy.

While studies determining the mechanical properties of ligaments or tendons in pregnant mammals are rare, so far no animal study (Rundgren, 1974; Hart et al., 2000) has detected a reduced stiffness in tendons or ligaments of peripheral joints with pregnancy, confirming our results. A study in pregnant rabbits determined the structural, material, and viscoelastic properties of the medial collateral ligament by in vitro material testing and found no effect of pregnancy on ligament stiffness (Hart et al., 2000). Similar research in pregnant rats demonstrated that the mechanical properties of the posterior cruciate ligament were in general not affected by pregnancy, with no changes in stiffness during gestation being detected. Only for the first three days in the PP a reduction in maximum load was recorded, returning to or above control levels thereafter (Rundgren, 1974). To our knowledge, this was also the only study that has ever investigated the mechanical properties of tendons during pregnancy, with no reduction in tendon stiffness of the rat musculus digiti quinti tendon being detected by material testing, neither during gestation nor during the PP. In our study, the average tendon stiffness remained constant during and after pregnancy. Thus, there is no evidence warranting the statement that changes in tendon tissue mechanical properties would increase the risk to suffer from tendon injuries during pregnancy. However, the variability in tendon stiffness values increased throughout pregnancy being 13 % larger postpartum compared to the EP. This indicates a highly individual response to the changed hormonal levels during pregnancy. Factors affecting the endocrine system in the PP, such as giving birth by cesarean section or breastfeeding (Atkinson and Leathem, 1946; Nissen et al., 1996), may have contributed to increased or reduced tendon stiffness in individual cases as well.

While in our study the mechanical properties of the patellar tendon did not change in general, pregnancy was found to affect its morphological properties. We detected a continuous increase in the tendon rest length measured at a 90 ° resting knee joint angle from EP to the postpartum measurement, which is also likely to be represented as a slight increase in the toe limit elongation. The implications of this change on the injury risk remain unclear. However, an increase in the tendon rest length may contribute to the increased joint laxity, which has frequently been reported for several peripheral joints in pregnant women. For the knee joint an increased amount of anterior tibial translation relative to the femur has been observed by Schauberger et al. (1996) using a clinical KT1000 arthrometer. Hypermobility measurements with gonio- and hyperextensometers in pregnant women demonstrated an increased range of motion in the elbow, the metacarpophalangeal joint of the index finger (Calguneri et al., 1982; Schauberger et al., 1996), the fourth finger (Östgaard et al., 1993), and the wrist (Marnach et al., 2003). A pregnancy-induced increase in ligament rest length could explain why Hart et al. (2000) found an increase in knee joint laxity in pregnant rabbits while the stiffness of the medial collateral ligament did not change. Joint laxity during pregnancy is assumed to lead to instability in the joints (Ritchie, 2003), which may be associated with impairments in postural stability and an increased incidence of falls (Dunning et al., 2003; McCrory et al., 2010a; Inanir et al., 2014). Thus, we cannot exclude that although tendon stiffness remained unchanged, the detected increase in tendon rest length may lead to an increased knee joint laxity. We may speculate that the increased rest length could result from effects due to hormonal changes and weight gain during pregnancy. It has been shown in vitro that increased levels of hRLX, which is elevated during pregnancy, potentiate creep effects in isolated rat tail tendons (Wood et al., 2003). An enhanced susceptibility to creep effects in combination with increased tendon load resulting from permanent weight gain during pregnancy may become apparent as long-term change in tendon morphology.

Apart from tendon properties we did not observe any effect of pregnancy on the knee extensor muscle strength. This is in contrast to Atay and Basalan Iz (2015) reporting a 9 % reduced handgrip strength at the end of pregnancy compared to the values being measured during the middle of pregnancy. The deviating findings may indicate that the upper and lower extremities undergo different adaptation processes during pregnancy. While loss in handgrip strength has been suggested to be primarily related to a reduced physical activity level (Atay and Basalan Iz, 2015) we may argue that leg strength has been maintained due to the pregnancy-induced increase in BM.

Thirty-two weeks after delivery the participants' strength levels were similar to non-pregnant controls. This result was expected since muscle strength at late PP has been reported to be almost consistent to the prior pregnancy status (Treuth et al., 2005).

It remains debatable whether the postpartum status actually reflects the prior pregnancy status. Fortunately, we were able to obtain data prior pregnancy in two women, allowing us to truly follow the development from prior pregnancy to the PP in these two data sets. Confirming our conclusions, both women did not show a reduction in tendon stiffness with pregnancy while demonstrating an increase in tendon rest length. With a 16 % increase in tendon rest length Woman-A appeared to be more sensitive to pregnancy-related changes while the increase in Woman-B was less with 6 %, emphasizing the individual response to hormonal changes.

A limitation of our study is that our experimental setup did not consider measures of the length-tension properties of the tendon. As criticized by Hoang et al. (2007) this challenges the assessment of the true rest length. However, since it was not the purpose of this study to investigate changes in tendon rest length, but to determine changes in tendon stiffness, a potential pretension at 90° knee joint angle was not taken into account. For a better understanding of the tendon properties during pregnancy, future studies should include measurements of tendon rest length changes in a passive condition as well as in more than one loading condition using different knee flexion positions. In addition, it may aid understanding to assess further parameters such as muscle stiffness in combination with tendon and ligament properties.

Another limitation is that our results are mostly applicable to women having their first child as 15 of our 19 pregnant participants have delivered for the first time. Since research in rats has shown effects of repeated pregnancies on tendon properties (Rundgren, 1974) a higher percentage of women having their second or third child may affect the results. Furthermore, we would like to point out that we focused on a single tendon of the human body. It remains to be established if our findings are transferable to other types of tendons, since hormonal changes during pregnancy have been found to be tendon-specific (Rundgren, 1974).

In conclusion, while the compliance of some ligaments such as the pelvic ligaments might change during pregnancy, we found no evidence to support the general assumption that tendons are subjected to the same change. Instead, our data provide evidence that patellar tendon stiffness is not affected by pregnancy. However, the progressive increase in the tendon rest length during and after pregnancy and its implication on the injury risk need to be further examined. Future studies are necessary to assess whether hypermobility in pregnant women may be related to a change in tendon or ligament rest length.

6.6 Data Availability

The data sets generated for this study can be found in the Dryad Digital Respository: https://doi.org/10.5061/dryad.5s0860n.

6.7 Author Contributions

KL conceived and designed the study. MEB and RM performed the data collection and further developed the advanced data analysis routines. MEB performed the data analysis and statistics, prepared figures, and wrote the first draft of this manuscript. LH assisted with the ethics application and was responsible for potential medical support of the subjects. KL and AA supervised the preparation of the manuscript and contributed to interpretation of the results. All authors approved the final manuscript and confirmed the responsibility of the content of this article.

6.8 Funding

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6.9 Acknowledgments

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7 Third article | The Effect of a Maternity Support Belt on Static Stability and Posture in Pregnant and Non-pregnant Women

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7.1 Abstract

Physical and hormonal changes during pregnancy are thought to affect balance and injury risk, with increased numbers of falls being reported. An MSB has been suggested to stabilize the pelvis and to enhance balance. The purpose of this study was therefore to investigate the effect of an MSB on postural stability in different trimesters of pregnancy.

Postural stability was assessed in T1 (n = 30), T2 (n = 30) and T3 (n = 30) of pregnancy and compared to non-pregnant controls (n = 30), using a portable force plate. Postural sway during quiescent standing with and without applying an MSB was characterized by analyzing path length, velocity, amplitudes and area. Subsequently, anterior and posterior LoS were determined.

Postural sway during quiescent standing did not change with pregnancy. However, LoS performance was reduced already in T1, before BM significantly increased. The MSB led to a small improvement in the LoS while slightly increasing postural sway in anterior-posterior direction and shifting the CoP posteriorly during quiescent standing.

While impairments in balance already occurred early in pregnancy before BM significantly increased, they were subtle and only measurable in exacerbated conditions. This challenges the assumed necessity of balance enhancing interventions in pregnant women. Although the MSB significantly affected body posture, the magnitude of the LoS improvement using the MSB was very small. Thus, it remains debatable if the MSB is a meaningful tool to increase balance during pregnancy.

Keywords:

gestation, balance, static, girdle, injury risk

7.2 Introduction

Physical activity has been shown to significantly reduce the risk of pregnancy-associated diseases e.g. high blood pressure, gestational diabetes and back pain (Nascimento et al., 2012; Ritchie, 2003), which is why current guidelines recommend moderate physical activity during pregnancy (Evenson et al., 2014). However, increased exercise and daily physical activity such as cycling to work or walking may increase the risk of falls (Vladutiu et al., 2010). It has been described that 27 % of 2847 investigated pregnant women have fallen during pregnancy (Dunning et al., 2003). Also, 64 % of 44 falls in pregnant women have led to injuries (Vladutiu et al., 2010).

Some of the physical and hormonal changes during pregnancy which affect the properties of the musculoskeletal system are also likely to influence the injury risk. The location of the CoM shifts in the posterior direction (Opala-Berdzik et al., 2010) and the gait pattern changes displayed by a decreased step width and an increased double support phase (Bertuit et al., 2015), which are known strategies to maintain balance. The spinal posture adapts leading to an increased thoracic kyphosis or lumbar lordosis (Betsch et al., 2015; Michonski et al., 2016). Furthermore, postural stability has been observed to change during pregnancy, with an increased postural sway in the anterior and posterior direction (Jang et al., 2008; Oliveira et al., 2009) and a decline of dynamic stability particularly in the advanced stages of pregnancy (Inanir et al., 2014) being reported.

Hormonal changes such as an increased hRLX levels have been shown to increase the laxity of ligaments in the pubic area (Ritchie, 2003). This contributes to the widening of the symphysis during childbirth (Ritchie, 2003; Vollestad et al., 2012). However, pelvic joint laxity is at the same time discussed to decrease the stability of the pelvis and to negatively influence postural stability.

An MSB, which is similar to a flexible and elastic kidney belt, has been shown to reduce pelvic mobility in pregnant women with pelvic girdle pain (Mens et al., 2006). Although the underlying mechanism is not yet sufficiently understood, it is believed that an MSB or another type of flexible and elastic belt induces a lateral compression on the articular surfaces of the sacroiliac joint (Mens et al., 2006), leading to a measureable reduction in the sagittal rotation (Sichting et al., 2014; Vleeming et al., 1992). Since the MSB may reduce mobility in the sacroiliac joint, it is also suggested to have a beneficial effect on postural stability. As yet, only one study has investigated the effect of an MSB on postural stability in pregnant women (Cakmak et al., 2014). This study did indeed detect a positive effect of the MSB on balance performance using the Biodex Balance System. Our study aims to confirm their results, while applying more commonly-used balance tests such as postural sway and LoS which allow the comparison with other studies on balance in pregnant women. In addition, we include a control group, to allow a more comprehensive interpretation of the results and randomize the test order to exclude sequence effects.

The aim of the present study is therefore to assess the effect of an MSB on postural stability in pregnant and non-pregnant women by investigating postural sway and LoS. We hypothesize that postural stability in pregnant women can be improved using an MSB.

7.3 Methods

7.3.1 Participants

For the study 90 healthy pregnant (30 $\pm$ 4 years) and 30 healthy non-pregnant women (28 $\pm$ 6 years) were recruited. The pregnant women were allocated to groups by trimesters according to WoP (T1: 1^{st} - 13^{th} WoP, T2: 14^{th} - 26^{th} WoP, T3: 27^{th} - 40^{th} WoP) (Gätje et al., 2015). Each group included 30 women and the mean WoP were 12 $\pm$ 2^{nd} WoP for T1, 22 $\pm$ 3^{rd} WoP for T2 and 32 $\pm$ 4^{th} WoP for T3. Women with a multiple pregnancy, pregnancy-associated symptoms such as gestational diabetes and present or past disorders potentially influencing postural stability were excluded from the study. The study had local ethics committee approval (Charité - Universitätsmedizin Berlin), and appropriate informed consent was obtained.

7.3.2 Study design

Postural stability was assessed in a static condition. The participants stood barefoot in a neutral position with a straight body posture and adjacent arms on a portable force plate (Type 9260AA6, 60 $\times$ 50 cm, Kistler, Switzerland). The feet were positioned straight at a predetermined line marked on the force plate and were kept parallel and hip-width apart.

The stability test started in a rest position, standing as motionless as possible. After 10 s the participants were instructed to lean in the anterior or posterior direction, moving their CoM safely within the maximum range, without changing their base of support. The maximum range had to be achieved within the next 10 s. Before the first measurement, the participants performed practice trials to ensure that the procedure of the test was sufficiently understood. Subsequently, the stability test was conducted twice with and without using an MSB in a random order. The MSB (Givereldi) is similar to a flexible and elastic kidney belt, which is made out of an elastic cotton fabric (Flack et al., 2015). Three different sizes of MSB, small, medium or large, were used. The belt was placed on the lower lumbar region and between the pubis and the umbilicus (Cakmak et al., 2014). The participants were instructed to fasten the MSB closely, while feeling comfortable. The correct fit was regulated by hook- and loop-fasteners.

The data were acquired with the software BioWare 5.3.0.7 using a sampling rate of 200 Hz. The data were filtered using a 10^{th} order digital low pass Butterworth filter at a 7 Hz cut-off frequency (Jang et al., 2008; Opala-Berdzik et al., 2014, 2015) and analyzed with MATLAB (R2012a, 64 Bit, The Mathworks, Natick, USA).

7.3.3 Postural sway

Postural sway was analyzed for the first 7.5 s standing in the rest position. The sway magnitude was determined by the total path length, the overall sway velocity, the sway amplitudes in A-P and M-L direction and by the sway area calculating the 95 % confidence ellipse (Duarte and Freitas, 2010).

7.3.4 Location of the center of mass

The location of the CoM during the rest position was estimated by the mean position of the CoP in the A-P direction. A CoP of 0 % foot length is located at the toes, 100 % of the foot length equates to the calcaneus.

7.3.5 Limits of stability

The LoS were assessed during leaning in the anterior and posterior directions. The approach of the CoP to the LoS was defined as the minimum distance (in cm and % foot length) between the maximum achieved range and the predetermined marking on the force plate representing the end of the base of support, which was the longest toe in the anterior direction and the calcaneus in the posterior direction (Moreno Catala et al., 2015; Qutubuddin et al., 2007). A smaller LoS indicates a better postural stability.

7.3.6 Statistical analysis

Statistical testing was performed using IBM SPSS Statistics (Version 21, 32 Bit, IBM, USA). The average of two trials was calculated for each parameter. To assess the effect of the WoP on postural stability, a linear regression analysis was conducted with and without application of the MSB, respectively. To detect differences in the characteristics between the regression lines the intersections of the 95 % confidence intervals of the coefficients and the constants were analyzed. Anthropometric differences between the groups (Controls, T1, T2, T3) were investigated using a one-way ANOVA and the Bonferroni post hoc test. Statistical analysis of the postural stability parameters was conducted using a two-way repeated measures ANOVA and the Bonferroni post hoc test, comparing the trimesters of pregnancy to the non-pregnant women with and without using the MSB. The effect size of the MSB was calculated using η^2. The alpha level was set at $\alpha = 0.05$.

7.4 Results

7.4.1 Body mass

BM and BMI in T2 (mass: $p = 0.008$, BMI: $p = 0.026$) and T3 (mass: $p < 0.001$, BMI: $p < 0.001$) were significantly higher compared to the controls, and in T3 (mass: $p = 0.006$, BMI: $p = 0.008$) significantly higher compared to T1 (Table 6).

7.4.2 Postural stability in the pregnant groups (T1, T2 and T3) and the controls

The LoS in T1 (ant: LoS $= 25.6 \pm 6.2$ % foot length, $p = 0.005$; post: LoS $= 21.4 \pm 5.8$ % foot length, $p = 0.005$) and T3 (ant: LoS $= 25.9 \pm 6.8$ % foot length, $p = 0.004$; post: LoS $= 20.9 \pm 3.7$ % foot length, $p = 0.008$) were significantly larger compared to the controls (ant: LoS $= 20.7 \pm 5.8$ % foot length, post: LoS $= 18.0 \pm 4.0$ % foot length), both in anterior and posterior directions (for absolute values see Figure 17). LoS in T2 (ant:

Table 6: Anthropometric data for the groups at different stages of pregnancy T1, T2 and T3 and the non-pregnant controls (means ± standard deviation).

Groups (each n=30)	**Age [year]**	**Body mass [kg]**	**Body height [cm]**	**Body mass index [kg/m^2]**
Controls	28 ± 6	62.0 ± 7.8	167 ± 7	22.1 ± 2.2
T1	31 ± 5	66.7 ± 10.4	168 ± 5	23.6 ± 3.6
T2	30 ± 4	71.0 ± 11.5 *	170 ± 6	24.7 ± 3.9 *
T3	30 ± 4	75.9 ± 11.2 *#	169 ± 6	26.5 ± 3.4 *#

*significantly different from the controls.

#significantly different from T1.

LoS = 24.5 ± 5.2 % foot length, post: LoS = 20.2 ± 4.3 % foot length) were slightly smaller compared to the other pregnant groups, and not significantly (ant: $p = 0.087$, post: $p = 0.17$) different from the controls.

Sway area, path length, sway amplitudes A-P and M-L (Figure 19) and sway velocity (C: 0.86 ± 0.2 cm/s, T1: 0.85 ± 0.2 cm/s, T2: 0.84 ± 0.2 cm/s, T3: 0.77 ± 0.2 cm/s) during quiescent standing did not significantly ($p > 0.05$) differ between the groups.

7.4.3 MSB effect

The MSB effect on postural stability was not affected by the WoP. The linear regression characteristics with and without MSB were similar (Figure 16), as shown by the intersections in the confidence intervals of the regression coefficients and constants (Table 7). Posterior LoS were significantly ($p = 0.042$, $\eta^2 = 0.035$) improved by 0.1 cm (0.5 % foot length) using the MSB (Figure 17B), while anterior LoS were not affected. Sway amplitude A-P significantly ($p = 0.036$, $\eta^2 = 0.038$) increased by 0.1 cm (Figure 19C) using the MSB while sway area, path length, sway amplitude M-L and sway velocity were not affected. In the rest position the MSB led to a significant ($p = 0.003$, $\eta^2 = 0.075$) posterior displacement of the CoP (Figure 18). On average the shift was 1.1 ± 0.4 % foot length ($\widehat{=}$ 2.6 ± 0.9 mm). No interaction between group and MSB condition was observed for any of the parameters ($p > 0.05$).

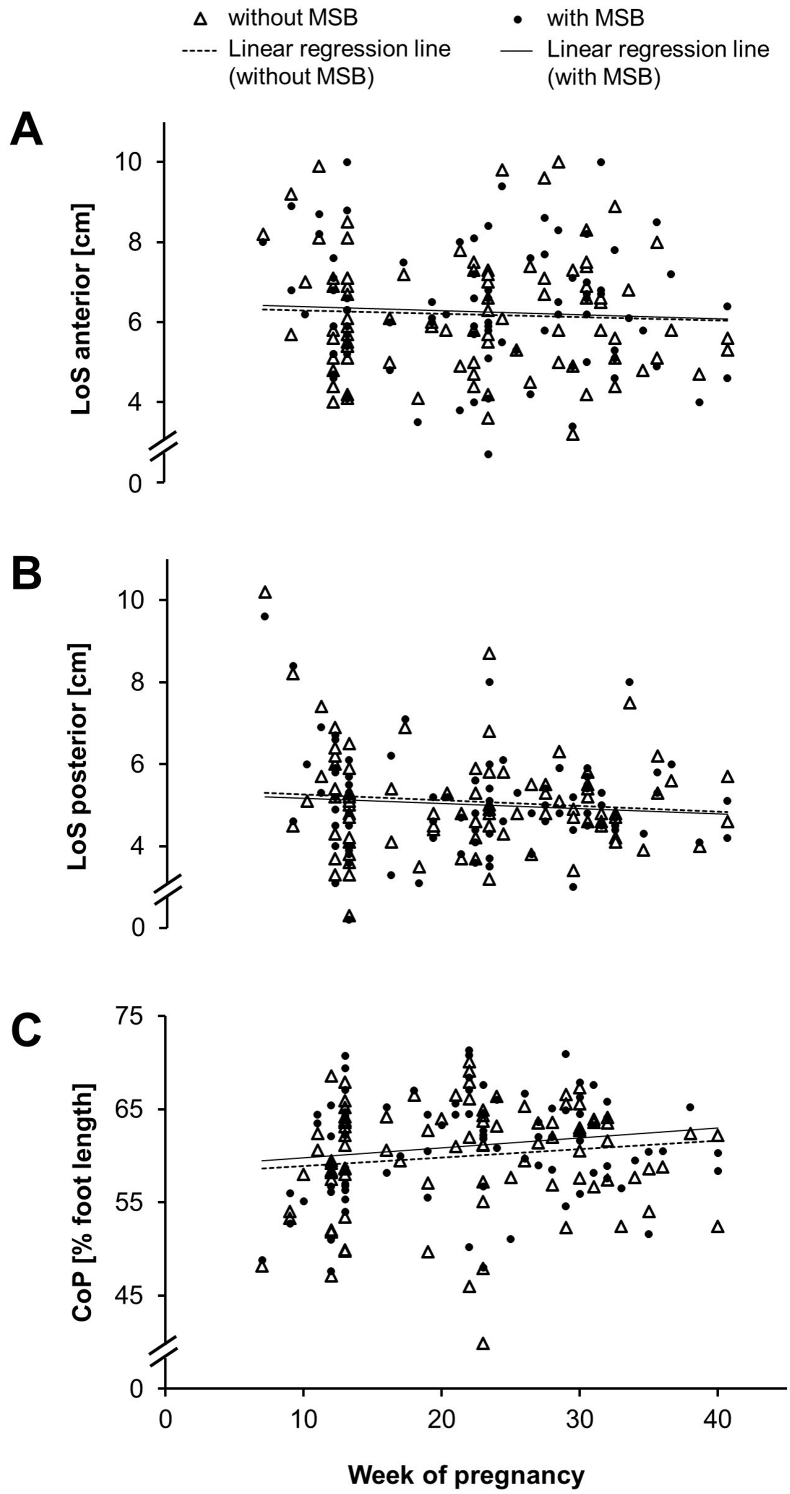

Figure 16: Anterior LoS (A), posterior LoS (B) and CoP locations in the rest position (C) in ninety pregnant women with and without MSB at different weeks of pregnancy. A CoP of 0 % foot length is located at the toes, 100 % foot length equates to the calcaneus.

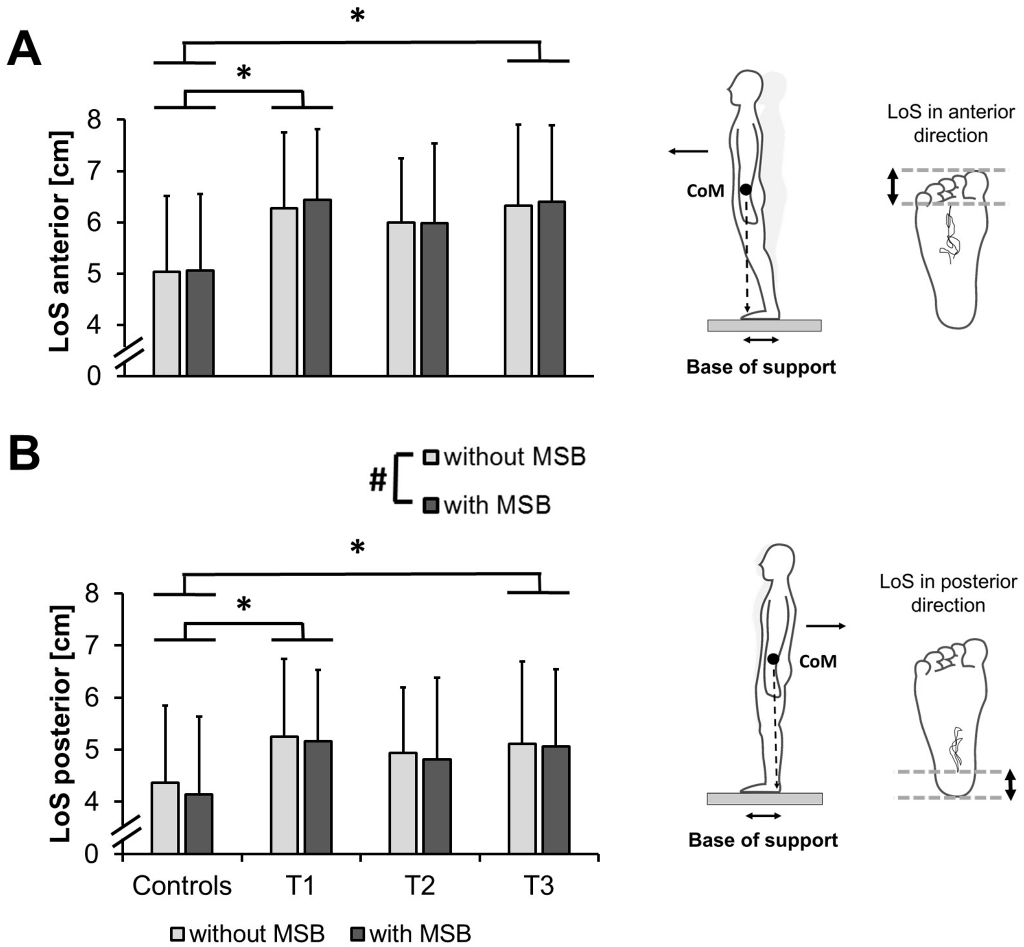

Figure 17: Anterior (A) and posterior (B) LoS with and without MSB at different stages of pregnancy (T1, T2 and T3) and in non-pregnant controls (*significantly different from the controls; #significant difference between the MSB conditions).

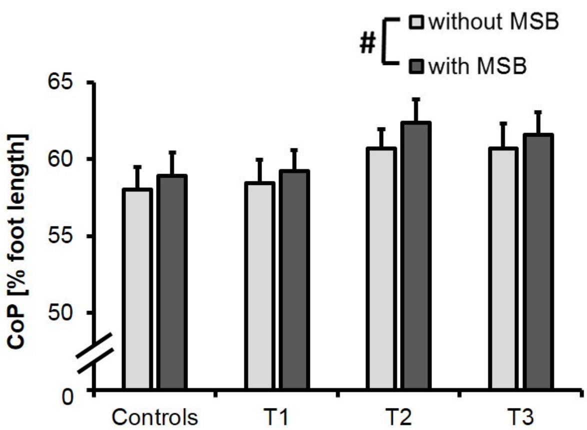

Figure 18: CoP locations in the rest position with and without MSB at different stages of pregnancy (T1, T2 and T3) and in non-pregnant controls (#significant difference between MSB conditions). A CoP of 0 % foot length is located at the toes, 100 % foot length equates to the calcaneus.

Table 7: Lower and upper limit of the 95 % confidence intervals of the regression coefficients for the postural stability parameters in ninety pregnant women with and without the MSB.

Parameter	Belt condition	Constant			Coefficient		
		Y-intercept	95% confidence interval		Slope	95% confidence interval	
			Lower limit	Upper limit		Lower limit	Upper limit
LoS anterior	without MSB	6.401	5.504	7.298	-0.009	-0.048	0.029
	with MSB	6.471	5.577	7.365	-0.010	-0.048	0.029
LoS posterior	without MSB	5.448	4.721	6.176	-0.016	-0.047	0.015
	with MSB	5.323	4.605	6.040	-0.014	-0.045	0.017
Sway area	without MSB	0.968	0.643	1.292	-0.006	-0.020	0.007
	with MSB	1.298	0.771	1.825	-0.016	-0.039	0.006
Path length	without MSB	6.816	5.959	7.673	-0.032	-0.069	0.005
	with MSB	7.015	6.061	7.968	-0.040	-0.080	0.001
Amplitude A-P	without MSB	1.236	1.043	1.428	-0.004	-0.013	0.004
	with MSB	1.515	1.265	1.765	-0.013	-0.023	-0.002
Amplitude M-L	without MSB	0.850	0.662	1.039	-0.006	-0.014	0.002
	with MSB	0.819	0.656	0.982	-0.006	-0.013	0.001
CoP	without MSB	58.258	54.794	61.721	0.081	-0.067	0.229
	with MSB	58.961	55.793	62.129	0.098	-0.037	0.234

7.5 Discussion

The MSB has small but significant effects on postural stability in pregnant and non-pregnant women, leading to a small reduction in the LoS, representing improved balance, while slightly increasing postural sway in the A-P direction, indicating impaired balance. Due to the conflicting results we cannot clearly reject or accept our hypothesis that the MSB leads to an improvement in postural stability. However, the fact that sway area, path length, sway amplitude in the M-L direction and sway velocity were not impaired by the MSB and that the improvement in posterior LoS appeared to be more systematic (similarly occurring in all groups) than the impairment in postural sway suggests that the positive effect of the MSB on postural stability prevails. If we accept the hypothesis it still remains debatable, if this subtle and barely detectable improvement in LoS with the MSB translates into a meaningful effect on postural stability in the daily life of pregnant women.

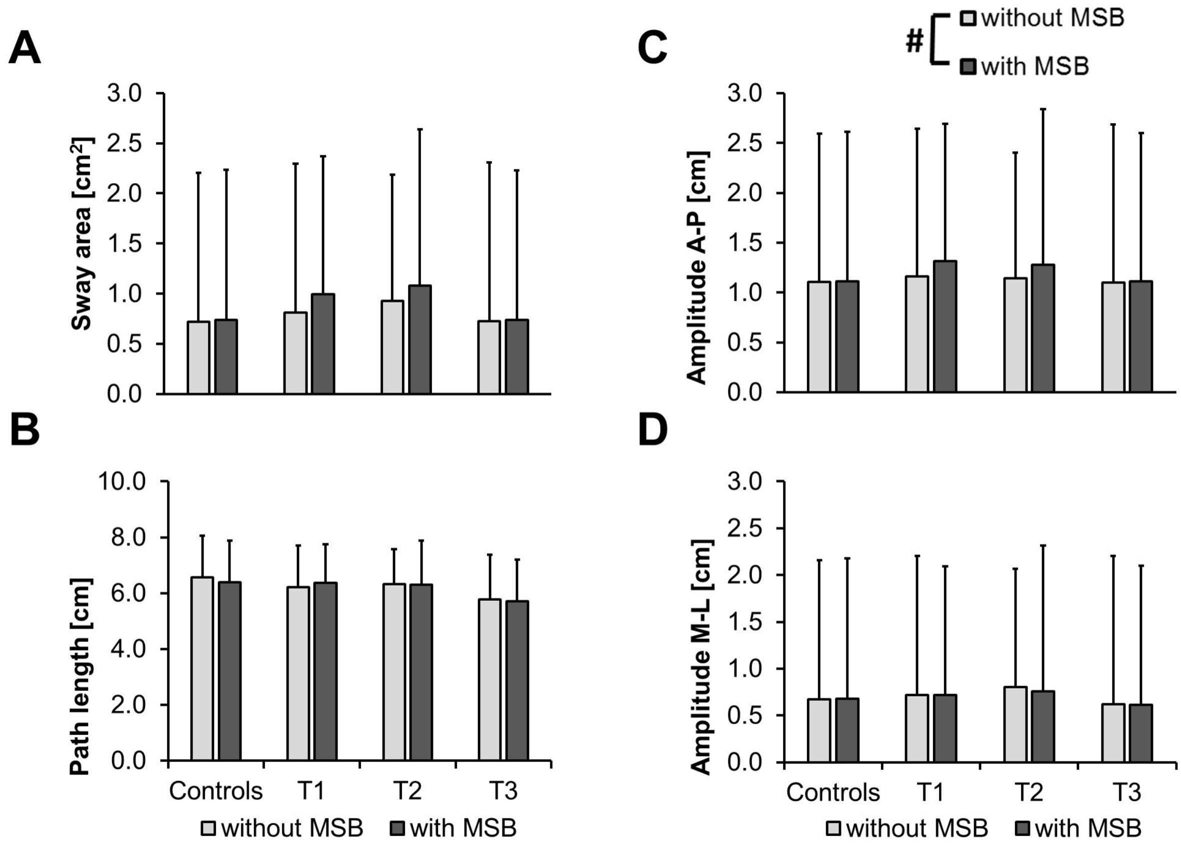

Figure 19: Sway area (A), path length (B) and sway amplitudes in anterior-posterior (C) and medio-lateral direction (D) with and without MSB at different stages of pregnancy (T1, T2 and T3) and in non-pregnant controls (#significant difference between the MSB conditions).

Our results, regarding a positive effect of an MSB on postural stability, are in line with one recent study conducted by (Cakmak et al., 2014) assessing postural stability in pregnant women using a Biodex Balance System. The authors of that study found a noticeable improvement in the stability scores with 16 % in A-P direction and 33 % in M-L direction using the MSB. The difference to our comparatively small improvement of 2 % in LoS performance might at least partially be explained by the different experimental design. Significant balance improvements may also result from sequence respectively learning effects related to the repeated execution of the balance test (Robbins et al., 2017; van Dieen et al., 2015). In order to avoid sequence effects interfering with postural stability measures in the current study, trials with and without using the MSB were performed in random order. However, it is questionable if an improvement in LoS performance of 2 % is physiologically relevant and if the MSB is an appropriate and meaningful strategy to increase balance in pregnant women. In comparison, an activity program with seniors held weekly for eight weeks, with each session lasting about 1 h, led to an improvement in the LoS of 9 % (Brouwer et al., 2003). Another exercise program with seniors, which focused on perturbations and was conducted twice weekly for 1.5 h over 14 weeks, even led to an improvement in LoS performance of 24 % (Hamed et al., 2018). While being far more time-consuming, in terms of balance improvement these exercise interventions appear to be far more effective compared to the MSB.

Apart from postural stability, we have shown that the MSB also affects body posture during quiescent standing in pregnant and non-pregnant women. The MSB led to a small shift of the CoP in the posterior direction, which is with 2.6 ± 0.9 mm half as large as the pregnancy-related shift of 6.6 ± 0.9 mm between pregnancy (T2 & T3) and non-pregnant controls. This MSB related shift in the CoP location may result from the reduced pelvic mobility (Damen et al., 2002; Mens et al., 2006). Furthermore, the MSB has been suggested to influence proprioception and to increase mental focus on the pelvis (Flack et al., 2015). Individuals may therefore become more aware of their body posture leading to a changed stance. This may also be associated to its effect in reducing pelvic girdle and back pain (Carr, 2003; Flack et al., 2015). The MSB related posterior shift of the CoP may furthermore explain the improved posterior LoS performance in our study, moving the CoM closer to the heels.

In comparison to non-pregnant women, postural stability during pregnancy has repeatedly been described to be reduced especially in the LP (Butler et al., 2006; Inanir et al., 2014; Jang et al., 2008). This has led to the assumption that weight gain as well as changes in body shape and composition during pregnancy may be relevant factors influencing balance (Inanir et al., 2014; Jang et al., 2008; Nagai et al., 2009). In the current study the LoS performance was found to be reduced already in the EP, before BM significantly increased. Thus, other physiological (McCrory et al., 2010b) or psychological factors such as an increased anxiety (Nagai et al., 2009) seem likely to have a more pronounced effect on postural stability than BM. Furthermore, postural stability performance during pregnancy might be task specific and depend on the degree of physical challenge. This may explain why most studies (Nagai et al., 2009; Oliveira et al., 2009; Opala-Berdzik et al., 2015) did not detect any differences when conducting a moderately challenging balance test such as motionless standing with open eyes. Interestingly, when maintaining balance was exacerbated by instructing the subjects to close their eyes, balance performance was significantly reduced in pregnant compared to non-pregnant women.

7.6 Conclusion

While the flexible and elastic MSB was found to affect postural stability in pregnant and non-pregnant women, it remains debatable if it is a meaningful tool to increase balance since the detected changes were marginal. Pregnant women demonstrated a slightly reduced postural stability in exacerbated circumstances compared to non-pregnant women. The mechanism behind this not progressing impairment in balance, which already occurred early in pregnancy before BM significantly increased, needs to be elucidated. Regarding the magnitude of the balance impairment, further studies of postural stability in pregnant women need to assess which degree of balance impairment necessitates postural stability enhancing interventions.

7.7 Conflict of interest

The authors have no conflicts of interest to disclose.

7.8 Acknowledgements

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7.9 Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jbiomech.2018.05.005.

8 Conclusion and perspectives

This doctoral thesis provides for the first time scientific information about changes in the properties of peripheral skeletal muscles and tendons during pregnancy. As there is a large deficit regarding the research of injury and fall risk factors related to pregnancy, our findings make an important contribution to filling this knowledge gap and may help to develop more appropriate recommendations regarding physical activity and injury prevention during pregnancy.

The aim of the first part of this thesis was to assess the functional, morphological, and mechanical properties of the muscle-tendon unit of the knee joint in pregnant women. In the first step, measurements were conducted to longitudinally investigate the properties of the knee extensors in the EP and LP as well as six months postpartum (First research article: Vastus Lateralis Architecture changes during Pregnancy - A longitudinal Study, chapter 5). Subsequently, we longitudinally investigated the mechanical properties of the patellar tendon (Second research article: Patellar Tendon Stiffness is not reduced during Pregnancy, chapter 6).
The aim of the second part was to analyze the effect of a flexible and elastic MSB on static postural stability in pregnant and non-pregnant women assessing postural sway and LoS (Third research article: The Effect of a Maternity Support Belt on Static Stability and Posture in Pregnant and Non-pregnant Women, chapter 7).

In the following paragraphs, the main outcomes of the conducted studies are discussed and potential implications for the risk of injury in pregnant women are derived. Separated by topic the limitations of the studies and the potential implications for scientific perspectives are addressed.

The outcomes of the conducted studies also provide relevant information for the assessment of the risk of injury in pregnant women and the development of appropriate prevention strategies. Final conclusions are highlighted in the last paragraph.

8.1 Changes in the muscle-tendon unit during pregnancy

To our knowledge, the study conducted in the first part of this thesis is the first study to provide information on the functional, morphological, and mechanical properties of the human muscle-tendon unit in the different stages of pregnancy. Our results demonstrate that the muscle morphology and tendon stiffness of the lower limbs are not negatively affected by pregnancy. Potential explanations for our outcomes and implications for the risk of injury in pregnant women are provided in the following paragraphs.

8.1.1 Knee extensor muscle properties

Regarding the knee extensor muscle morphology, we found an increase in the fascicle angle and muscle thickness from the EP to LP. These alterations point towards a radial adaptation of the vastus lateralis muscle indicative of muscle hypertrophy. As there are no comparable studies investigating potential factors leading to muscle growth in pregnant women or gestating animals, in our research article (chapter 5) we discussed several factors affecting muscle architecture.

One of these factors is the increased BM as the increase in muscle thickness of 9 % in the LP was similar to the BM increase of 10 %. However, our statistical analysis demonstrated that the increased BM during pregnancy is unlikely to be the only factor triggering adaptation of the muscle.
Alternatively, we can also assume that conditions during pregnancy such as changes in the endocrine system can foster skeletal muscle hypertrophy since improved regenerative processes in skeletal muscles during pregnancy have been described, at least in animal models (Falick Michaeli et al., 2015). Research on postmenopausal monozygotic twins revealed that skeletal muscles do more likely respond to mechanical loading when a hormone therapy with sevenfold levels of estrogen is given (Ronkainen et al., 2009). Thus, pregnancy with 40 times higher levels of estrogen compared to non-pregnant women (Martin and Behbehani, 2006) may be a favorable metabolic condition which promotes adaptation to training stimuli and an increased BM.

In our research article, we further suggested that water retention in the intracellular space may have caused a thickening of the muscle fibers resulting in a measurable increase in muscle thickness. However, again no correlation has been found between the parameters. In conjunction with the body water assessment, it needs to be mentioned that we were not able to consider the content of the amniotic fluid. This may have affected our results. Another limitation is that we did not control the fluid intake in our pregnant participants. However, our results demonstrate that variation in the ICW and ECW of a pregnant woman was rather small at each measurement time point. In contrast, differences between pregnant women were much larger (Figure 10A, B) which is why we would not expect an effect of hydration differences on the muscle properties.

We speculate that changes in the muscle architecture are attributed to pregnancy-related changes in body posture. It seems conclusive that alterations in body shape during pregnancy are accompanied by adaptive mechanisms of the body to maintain balance. As a compensatory effect for the increased anterior load caused by the growing fetus, pregnant women in the LP have been found to adapt their body posture by shifting the CoM 4.0 - 6.6 mm in the posterior direction during upright standing (Opala-Berdzik et al., 2010; Bey et al., 2018). During upright standing the muscle fibers of the knee extensors are lengthened beyond the optimum of the force-length relationship (Houtz et al., 1957). An adaptive increase in the hip angle in pregnant women might further lengthen muscle fibers impairing the unfavorable condition for force production. Thus, the muscle may rely on increased muscular activity to compensate for the impairment in force production. An increased muscle activity could then contribute to radial adaptation in the vastus lateralis muscle. However, if the muscle is continuously active at a different part of the force-length relationship, a change in muscle FL is likely (Sharifnezhad et al., 2014; Herzog et al., 1991). As we did not find any changes in muscle FL, it appears that this stimulus is not sufficiently high to promote a longitudinal adaptation.

It can be summarized that the pregnancy-induced change in muscle architecture is unlikely to be attributed to a single factor. Further research is necessary to clarify which pregnancy-associated combination of changes in the endocrine system, BM, and body composition contributes to this morphological alteration.

Apart from changes in muscle morphology the functional properties of the knee extensors did not change during pregnancy. The mechanism underlying this effect needs to be further investigated as our observed increase in muscle thickness may point towards muscle hypertrophy and, thus, to an increased force capability. However, the absolute muscle strength remained constant from the EP to LP and did not differ from the postpartum status or that of the non-pregnant women. This contrasts to findings that reported the upper extremities becoming weaker during pregnancy (Atay and Basalan Iz, 2015). We argue that the lower extremities are subjected to a different adaptation process than the upper extremities.

The constant strength performance of the knee extensors despite increased muscle thickness during pregnancy may be attributed to a neural adaptation that is manifested as an increased coactivation of the knee flexors. However, we detected a marginal but not statistically significant increase (+ 1.5 %) in the coactivation of the knee flexors from the EP to LP (EP: 8.9 ± 4.2 %, LP: 10.4 ± 5.4 %, $p = 0.259$, unpublished data, see appendix A.1). Thus, the constant strength performance is unlikely to be the result of an increased force capability of the antagonists.

It is possible that a reduced physical activity level may have sightly reduced the muscle strength performance as we did not control the physical activity level in our participants (Atay and Basalan Iz, 2015). However, even when our pregnant participants were less active in the LP compared to the EP, this did not contribute to a meaningful loss in strength as has been shown for the upper extremities (Atay and Basalan Iz, 2015).
A slight reduction in the muscle strength might also be attributed to a pregnancy-related fast-to-slow fiber type shift (Bisch et al., 2006). As primarily fast fibers are involved in force production during the ramp contractions (Gollnick et al., 1974), a reduced number of fast fibers may have diminished the force capabilities of the knee extensors in our participants.
Psychological factors such as not feeling confident enough to perform a maximum isometric ramp contraction on the dynamometer in the LP might also have affected the force capabilities of our participants. Furthermore, anxiety may also have influenced the results as increased levels of axiety are a common side effect during pregnancy (Dennis et al., 2017; Nakic Rados et al., 2018).

Finally, muscle strength during pregnancy may have been partly affected by a calcium deficiency which is associated with the high prevalence of cramps in the calves during pregnancy (Ireland and Ott, 2000; Hammar et al., 1981). As reported by Herzog et al. (2015), calcium is essential for force production as it regulates stability and stiffness of titin upon activation. If the calcium level was reduced in our pregnant participants, this may have led to a unfavorable stretch state of titin impairing the strength level.

Thus, there is evidence to suggest that pregnancy provides conditions that may be favorable for retaining muscle strength in the lower extremities. Both the increased BM and changes in the hormonal milieu are likely to trigger muscle growth. In contrast, changes in the mental state during pregnancy seem most likely to counteract the improved muscle force capabilities during contraction. However, from an evolutionary perspective a reduction in the lower extremities' strength seems to be unlikely. This may explain why we did not detect any statistical differences in muscle strength between pregnant fallers (six from 19 women, 32 %) and non-fallers ($p > 0.05$, unpublished data, see appendix A.2). Nevertheless, when normalizing muscle strength to BM we detected a decrease in the LP. Future studies to investigate whether in the event of balance perturbations the legs are actually strong enough to maintain balance are needed. As balance ability has frequently been shown to decrease during pregnancy (Oliveira et al., 2009; Inanir et al., 2014; Bey et al., 2018), while pregnant women have to meet the requirements for a greater physical demand due to the increased BM, a loss in the lower extremities' muscle strength relative to BM seems likely to be a crucial factor for the increased risk of injury during pregnancy.

Summing up, the lack of absolute muscle strength improvements despite the increased physical demand during pregnancy suggests an increased risk of injury in pregnant women. However, at the same time pregnancy is likely to provide favorable metabolic conditions promoting muscle adaptation to training and mechanical loading (Falick Michaeli et al., 2015; Rundgren, 1974; Delmonico et al., 2009). Pregnancy appears to be a suitable period of a woman's life to be physically active and to continue exercising. Thus, especially in the case of sedentary pregnant women who do not meet the minimum national recommendation of 30 minutes moderate physical activity a day (Mudd et al., 2009; Dobson et al., 2012; Gaston et al., 2012; Gjestland et al., 2013; Juhl et al., 2012; Zhang and

Savitz, 1996; Sternfeld et al., 1995) the positive effect of pregnancy on muscle adaptation may be a possible key motivator for their participation in a physical activity program.

8.1.2 Patellar tendon properties

With our measurements, we demonstrated that the mechanical properties of the patellar tendon are not affected by pregnancy. Tendon stiffness was constant during and after pregnancy which is in line with findings from a previous animal study that did not observe any reduction in the modulus of elasticity of the musculus digiti quinti tendon in gestating rats (Rundgren, 1974). Another animal study did also not found a reduction in stiffness of the medial collateral ligament in gestating rabbits (Hart et al., 2000). While the compliance of pelvic ligaments can change during pregnancy (Ritchie, 2003; Borg-Stein et al., 2005; Rundgren, 1974; Perezgrovas and Anderson, 1982; Musah et al., 1986), the assumption that peripheral ligaments and tendons are subjected to the same change (Danning, 2013; Nordin and Frankel, 2001; Martin et al., 2015; Blott, 2010; Klausmann, 2002; Engels et al., 2009) is, thus, not correct.
With regard to the pregnancy-induced increase in the thickness and the pennation angle of the vastus lateralis muscle, we argue that conditions during pregnancy are accompanied by stimuli suited to affect the muscle properties (see chapter 8.1.1). These stimuli, however, are not sufficient to promote adaptations in the tendinous tissue.

It needs to be stated that in individual cases tendon stiffness increased or decreased throughout pregnancy. Postpartum stiffness values were 13 % greater than values being measured in the EP. This suggests an individual response to the changed hormonal milieu in the PP. Giving birth by cesarean section or breastfeeding (Atkinson and Leathem, 1946; Nissen et al., 1996) may be potential factors that affect the endocrine system and possibly contribute to the variability in the measured tendon stiffness values.

Even though we did not establish hormone levels in our participants, our results indicate that high concentrations of serum estrogen and hRLX during pregnancy do not necessarily reduce tendon stiffness. Contrasting observations have been described for elevated levels of estrogen and hRLX during the menstrual cycle in young females (Pearson et al., 2011; Hansen et al., 2013) even though hormone levels during the menstrual cycle are negligible compared to levels during pregnancy (Charlton et al., 2001; Pearson et al., 2011; Martin and Behbehani, 2006).

An unchanged stiffness of the patellar tendon may indicate that pregnancy does not negatively affect muscle fascicle shortening and force production. Thus, impairments in balance ability and the incidence of falls in pregnant women (Pearson et al., 2011; McCrory et al., 2010a) are most likely not related to this factor. Indeed, there is no significant difference in the patellar tendon stiffness of the pregnant fallers and non-fallers (fallers: EP = 1.086 ± 107 N/mm; LP = 1.204 ± 124 N/mm; non-fallers: EP = 1.050 ± 216 N/mm; LP = 972 ± 240 N/mm; $p > 0.05$, unpublished data, see appendix A.3).

Furthermore, it seems unlikely that pregnancy increases the risk of tendon damage. Tendon strain in our pregnant study population was 7.3 % on average which is below the range of excessive strain values of 8.5 - 12 % that is commonly associated with ruptures of the tendon tissue (LaCroix et al., 2013; Wang et al., 2013; Wren et al., 2003). Thus, the warnings regarding a generally increased risk of compliance-associated tendon injuries (Blott, 2010; Klausmann, 2002; Engels et al., 2009; Kainer and Nolden, 2015; Klausmann, 2002; Danning, 2013) during pregnancy do not appear to be justified.

While in our study population the mechanical properties of the patellar tendon did not change during pregnancy, we detected an increase in the tendon length during and after pregnancy that was 5 % greater postpartum than in the EP. The postpartum tendon length was 8 % larger than that from the non-pregnant controls. We do not know whether the detected increase in the PP occurred during pregnancy and then continued in the PP as we conducted two measurements during pregnancy and one measurement six months after delivery. However, future studies with a larger number of measurements may help to identify the exact time line of the tendon length increase.

The increase in patellar tendon length may be associated with the increased knee joint laxity that is repeatedly observed in pregnant women (Schauberger et al., 1996; Dumas and Reid, 1997; Hart et al., 2000; Chu et al., 2019). The relationship between these parameters might explain why Hart et al. (2000) detected increased knee joint laxity in gestating rabbits while stiffness of the medial collateral ligament was not reduced. It seems important to further investigate this effect since increased joint laxity is deemed to be accompanied by an increased risk of ligament injuries (Kainer and Nolden, 2015; Klausmann, 2002; Blott, 2010; Engels et al., 2009; Lutter and Lee, 1993; Kiechle, 2011; Eberlein, 2008; Drewes, 2011).

Hormonal changes seem to have contributed to alterations in the tendon morphology. In rat tail tendons, elevated hRLX levels have been found to increase the viscoelastic response to load and tissue length (Wood et al., 2003). This effect may have been potentiated by the permanent weight gain.

Pregnancy is further associated with a fast-to-slow fiber type shift. However, as slow fibers are associated with an increased stiffness in muscle tissue (Bisch et al., 2006) an increase in patellar tendon length might compensate for this mechanism in order to maintain joint mobility during pregnancy. The mechanism underlying increased tendon length requires further research.

In conclusion, while pregnancy is likely to be accompanied by stimuli affecting the knee extensor muscle properties (Bey et al., 2019b), these stimuli are not sufficient to promote adaptations in the patellar tendon mechanical properties. However, while the mechanical properties of the patellar tendon did not change during pregnancy, we detected an increase in the tendon length during and after pregnancy. Factors leading to this change need to be investigated in future studies. Hormonal changes in conjunction with increased mechanical loading due to an increased BM may have contributed to the morphological change in the tendinous tissue (Wood et al., 2003).

The increase in patellar tendon length may be associated with increased knee joint laxity (Schauberger et al., 1996; Dumas and Reid, 1997; Lindgren and Kristiansson, 2014; Chu et al., 2019; Charlton et al., 2001) and the commonly-accompanied increased risk of ligament injuries (Blott, 2010; Klausmann, 2002; Lutter and Lee, 1993; Kiechle, 2011; Engels et al., 2009; Eberlein, 2008; Drewes, 2011).

8.1.3 Limitations of the study

One limitation of our conducted study is that we did not measure the prior pregnancy status. Thus, despite the evidence that hRLX levels return to pre-pregnancy levels by two weeks postpartum (Schauberger et al., 1996) it remains unclear whether our data from the 32 ± 9^{th} week postpartum actually reflect the status of the pre-pregnancy period. Fortunately, for two of our participants we were able to record data prior pregnancy. Both data sets confirm the assumption that the functional and morphological parameters of the knee extensor muscles as well as the mechanical properties of the patellar tendon in the PP and in the pre-pregnancy period are similar.

It also needs to be mentioned that the data on our non-pregnant women mostly reflect tendon mechanical properties of non-oral contraceptive users, as eleven of our 15 non-pregnant women did not use hormonal contraception. Compared to oral contraceptive users, the tendon tissue of non-users has been found to be more sensitive to fluctuating levels of estrogen (Hansen et al., 2013).

Regarding the pregnant group, it needs to be pointed out that our findings are mostly applicable to women having their first child, as 15 of our 19 pregnant women were giving birth for the first time. Research in rats has shown that an increased number of pregnancies is likely to influence the tendon mechanical properties (Rundgren, 1974).

Another limitation is that we assessed the properties of a single tendon. It is debatable whether our findings are transferable to other types of tendons, since hormonal effects during pregnancy have been described to be tendon-specific (Rundgren, 1974).

From a methodological point of view, it needs to be stated that we determined knee joint moments during the isometric ramp contractions in the sagittal plane only while kinetic data in the coronal and transverse plane was not considered. This might have led to an underestimation of the tendon force. Furthermore, for tendon force calculation the tendon moment arm was estimated following the approach of Herzog and Read (1993) who provide regression coefficients for predicting moment arms as a function of different knee joint angles (Mersmann et al., 2016). Thus, we do not know the actual length of the moment arm of our participants at rest or during muscle contraction. Nevertheless, as the absence of these methodological adjustments is considered systematic error, this limitation is unlikely to affect the informative value of our findings.

In the assessment of tendon stiffness, we did not consider a potential pretension at 90 ° knee joint angle either as this would have required further measurements, e.g. in another knee joint angle. However, the duration of our experiment was quite long in order to accurately measure tendon stiffness, i.e. there were at least five trials that incorporated a motion capture system to take axes misalignments into account (Arampatzis et al., 2004; Schulze et al., 2012). Additional measurements would have been demanding for our participants. Furthermore, we decided to measure at a 90 ° knee joint angle as we intended to allow for a better comparison with two previous studies on the effect of female hormones on patellar tendon stiffness (Pearson et al., 2011; Hansen et al., 2013), using the same knee flexion position. However, to facilitate a more comprehensive understanding of changes in the patellar tendon properties, in future studies the assessment of the tendon rest length in more than one loading condition and in different knee flexion positions or even in a passive condition should be considered. In addition to tendon and ligament properties it may also be helpful to determine muscle stiffness.

8.2 The effect of a maternity support belt on static postural stability during pregnancy

The study conducted in the second part of this thesis confirms impairments in postural stability in pregnant women reported in the literature (Inanir et al., 2014; Jang et al., 2008; Butler et al., 2006; Nagai et al., 2009; Ribas and Guirro, 2007) and the positive effect of a flexible and elastic MSB on balance ability. However, the established effects have been found to be marginal and are, thus, unlikely to be physiologically relevant or associated with injuries and falls during pregnancy. Further details are highlighted in the following paragraphs.

8.2.1 Impairments in postural stability during pregnancy

In agreement with our findings, it has repeatedly been shown that pregnancy is accompanied by impaired postural stability (Inanir et al., 2014; Jang et al., 2008; Butler et al., 2006; Nagai et al., 2009; Ribas and Guirro, 2007). However, in contrast to previous studies (Jang et al., 2008; Ribas and Guirro, 2007; Inanir et al., 2014; Butler et al., 2006) that reported a progressive decline over the course of the different stages of pregnancy, impairments in static postural stability assessed by the anterior and posterior LoS occurred already early in pregnancy and remained on the same level for the advanced stages of pregnancy.
Since impairments in the LoS are already detectable in T1, before the BM significantly increases, weight gain and changes in body shape are unlikely to be major contributors to the reduced balance ability. Other factors seem to have a more pronounced effect.

A loss in the muscle strength of the lower extremities (Moreland et al., 2004; McCrory et al., 2010b; Opala-Berdzik et al., 2014; McCrory et al., 2010a) has repeatedly been assumed to diminish balance ability in pregnant women. However, as described in our first research article (Vastus Lateralis Architecture changes during Pregnancy - a Longitudinal Study, chapter 5), there is no clear evidence to suggest that the muscle strength of the lower limb decreases during pregnancy. Increases in thickness and pennation angle of the vastus lateralis muscle instead indicate muscle hypertrophy. Therefore, functional and morphological alterations in the knee extensors are unlikely to contribute to a decline in balance ability in pregnant women.

We speculate that increased joint mobility (Dragoo et al., 2011a,b; Lubahn et al., 2006; Ritchie, 2003; Borg-Stein et al., 2005; Cakmak et al., 2014; Inanir et al., 2014) due to more compliant ligaments or a lengthening of tendons in the lower body (Bey et al., 2019a) can negatively affect overall postural stability. A pregnancy-related lengthening of the abdominal muscles associated with impaired functional properties and a reduced ability to stabilize pelvis (Gilleard and Brown, 1996) may further diminish joint stability. The next step might be to clarify which combination of factors is most likely to reduce balance ability in pregnant women. Further studies could also consider a documentation of psychological changes during pregnancy. Increased anxiety levels are a common negative side effect during pregnancy and have been found to increase postural sway in pregnant women (Nagai et al., 2009).

Even though balance ability in pregnant women was significantly reduced as compared to non-pregnant women, we found that the magnitude of balance impairments was marginal. Further studies also need to investigate which degree of balance impairment necessitates interventions to improve balance ability in pregnant women.

Furthermore, balance impairments were only detectable in the LoS test when balance maintenance was exacerbated. In contrast, no changes in postural sway were observed during motionless upright standing. This finding aligns with observations from previous studies (Nagai et al., 2009; Oliveira et al., 2009; Opala-Berdzik et al., 2015) which also reported balance impairments during pregnancy primarily for balance conditions requiring an increased physical challenge such as motionless standing with eyes closed. We assume that balance impairments are intensified in dynamic and unstable conditions as a pregnancy-related fast-to-slow fiber type shift in the muscles (Vesentini et al., 2018) can lead to reduced reaction times in response to perturbations. However, the findings from the available literature that focus on dynamic postural stability during pregnancy are inconsistent and do not allow to draw clear conclusions (Inanir et al., 2014; McCrory et al., 2010a; Cakmak et al., 2014; Ersal et al., 2014). McCrory et al. (2010a) found better reaction times in response to translational perturbations in pregnant fallers than in non-fallers and non-pregnant women. Ersal et al. (2014) also detected improved responses to A-P perturbations in pregnant fallers compared to the other groups. In contrast, two other research groups established impaired dynamic postural stability in pregnant women in T3 compared to non-pregnant women (Inanir et al., 2014) and a progressive increase in the risk of falling during pregnancy (Cakmak et al., 2014).

While balance tests in dynamic conditions are commonly accompanied by individual differences in balance control strategies (e.g. different compensatory movements with the arms or a different size of the base of support), our conducted LoS test enables a more standardized measurement. This enhances the comparability of the data between participants. Better comparability was also the reason why we specified a hip-width standing position even though women are known to increase their step width over the course of pregnancy (Jang et al., 2008; Nagai et al., 2009; Dumas and Reid, 1997).

Summing up, pregnancy is accompanied by impairments in static postural stability that occur from the EP and regardless of the increased BM. However, impairments in postural stability are marginal and only detectable in exacerbated conditions. This leads to the question of whether balance enhancing interventions are actually needed in pregnant women.

8.2.2 Implications for the risk of falling during pregnancy

Based on the data presented in our published research article (The Effect of a Maternity Support Belt on Static Stability and Posture in Pregnant and Non-pregnant Women, chapter 7), we cannot calculate the effect of reduced LoS performance on the risk of falling during pregnancy. However, when we split our participants into fallers and non-fallers, we did not find any significant differences in the LoS performance between fallers and non-fallers, in either the pregnant or the non-pregnant women (unpublished data, see appendix A.4). Therefore, we suggest that a reduction in the LoS performance does not lead to a higher number of falls during pregnancy.

Looking at the frequency of falls, around 25 % of our participants fell during pregnancy (unpublished data, see appendix A.5), which is similarly high to the incidence of falls reported in the literature, i.e. 27 % (Dunning et al., 2010). However, 53 % of our non-pregnant controls fell, which is a significantly larger percentage. As Jang et al. (2008) also reported a higher percentage of falls for the non-pregnant women, i.e. 47 %, this raises the question of whether the risk of falling during pregnancy has been overestimated in general. The incidence of falls is mainly derived from one large cohort study from Dunning et al. (2010) which did not contrast this number with a reference value from a non-pregnant control group or the same group during another period of time, e.g. after delivery.

Our study also included comprehensive information regarding daily physical activity and exercise program since sedentary pregnant women have been reported to be more likely to expect a fall than pregnant exercisers (McCrory et al., 2010a). The data demonstrate that both groups, the pregnant and the non-pregnant women, were similarly active as they spent on average 225 minutes a week walking or bicycling from a to b (unpublished data, see appendix A.5). However, the exercise program of the pregnant women was 105 minutes a week and therefore significantly shorter than that of the non-pregnant women who spent 338 minutes on average on exercising (unpublished data, see appendix A.5). Even though most of our participants were more active in their daily lives than the time recommended by the WHO, i.e. 150 minutes a week (WHO, 2016), the difference in the time spent purely exercising, i.e. 233 minutes, between our pregnant women and non-pregnant controls and the consequences thereof on the impaired LoS performance in the pregnant group should be further investigated. Lower intensity physical activity or different types of exercise activities may have also affected balance ability.

In conclusion, while pregnant women demonstrate marginal impairment in the LoS as compared to non-pregnant women, this did not lead to a higher number of falls. A higher number of falls occurred in the non-pregnant women which may be due to higher intensity physical activity or other types of exercise activities. The amount of daily physical activity did not affect the number of falls in our participants. However, it remains to be clarified whether a shorter exercise program in the pregnant group might have affected the incidence of falls during pregnancy.

8.2.3 The effect of a maternity support belt on static postural stability during pregnancy

Despite a slight decline in static postural stability during pregnancy we found that a flexible and elastic MSB improves postural stability. This aligns with the findings of Cakmak et al. (2014) which determined stability and fall risk scores in pregnant women using a Biodex Balance System. However, the positive effect, i.e. a 2 % improvement, in our study was marginal and only measurable for the posterior LoS. It remains unclear whether the MSB is a meaningful device to improve stability during daily physical activities. Other methods such as exercise interventions may be more effective since a 14-week exercise program in seniors was found to improve the LoS performance by 24 % (Hamed et al., 2018). However, due to its relatively small effect we question whether the MSB is an appropriate strategy for the prevention of falls in pregnant women even though this has been postulated by Cakmak et al. (2014).

During motionless upright standing, the MSB was found to shift the CoP in the posterior direction by 2.6 ± 0.9 mm in both the pregnant and the non-pregnant women. This change may also contribute to the positive MSB effect on the posterior LoS performance, reducing the distance of the CoP to the heels. The shift of the CoP in the posterior direction may also be related to a reduced mobility of the pelvic joints (Damen et al., 2002; Mens et al., 2006) as flexible and elastic belts are generally assumed to compress the articular surfaces of the sacroiliac joint (Mens et al., 2006), thereby reducing joint mobility in the sagittal plane (Sichting et al., 2014; Vleeming et al., 1992). The MSB may further increase the focus on the pelvis or lead to an altered proprioception resulting in an unconscious change in body posture. Changed body posture, in turn, may be accompanied by the relief of the lower back. This may be associated with the high number of pregnant women reporting reduced lower back and pelvic girdle pain when using the MSB (Carr, 2003; Flack et al., 2015).

In summary, a flexible and elastic MSB slightly improves static postural stability in pregnant women. However, it remains debatable whether the MSB is actually a meaningful tool to considerably enhance balance ability during pregnancy. In pregnant and non-pregnant women, the MSB leads to a shift of the CoM in the posterior direction. This change is possibly associated with its effect in reducing pelvic girdle pain and back pain (Carr, 2003; Flack et al., 2015).

8.3 Final conclusions

The outcomes highlighted in the previous paragraphs reveal that there is actually no evidence to suggest that pregnancy induces functional, morphological or mechanical properties of the muscle-tendon unit of the knee joint that would profoundly increase injury risk. Against the assumptions frequently stated in the literature, pregnancy does not reduce tendon stiffness. Concerns may arise regarding the continuous increase in the tendon length during pregnancy (Bey et al., 2019a); its association with peripheral joint laxity and connective tissue injuries needs to be further investigated. Further the lack of a functional adaptation of the lower extremities despite a greater physical demand due to the increased BM may indicate a potential risk of losing balance. However, we argue that exercise during pregnancy, and especially moderate strength training, may be advantageous to counteract these risk factors. Strength training may increase the stabilization of the joints in order to prevent twisting and extensive torsions (Lewkonia, 1987). At the same time, it may help to enhance the ability to more easily regain the stability of the heavier body in the event of a balance loss and to prevent a fall.

As physical activity during pregnancy is known to foster the healthy development of the fetus, reduce the risk of pregnancy-associated diseases, and improve overall well-being and endurance for delivery (Montoya Arizabaleta et al., 2010; WHO, 2016; DeMaio and Magann, 2009; Jackson et al., 1995; Clapp, 2003; Owe et al., 2016) we strongly recommend that pregnant women are to encouraged to continue exercising and being active. However, it should be noted that the adherence to the WHO and ACOG guidelines (ACOG, 2015; WHO, 2016) regarding intensity and the types of sport should be taken into consideration. High-intensity exercise should be avoided as excessive physical activity can lead to overheating (Sasaki et al., 1995) and reduced blood flow to the placenta (Rauramo and Forss, 1988) which impair fetal development. Contact sports such as soccer and basketball as well as activities with impact such as horse riding are associated with preterm birth and maternal injuries (ACOG, 2015). It also needs to be stated that our recommendation regarding physical activity is only applicable for healthy pregnant women without contraindications.

As the number of women who participate in physical activity during pregnancy is small (Mudd et al., 2009; Dobson et al., 2012; Gaston et al., 2012; Gjestland et al., 2013; Juhl et al., 2012; Zhang and Savitz, 1996; Sternfeld et al., 1995), it is extremely important to improve the negative attitude toward physical activity in pregnant women. If we are to make recommendations, we propose four different solution approaches to possibly increase the participation in physical activity:

First, we feel that the quantity and quality of information in pregnancy guidelines, text books, and the media needs to be considerably improved as these are an important source of information for pregnant women (Cannella et al., 2010). We suggest that there should always be a reliable scientific basis for all information provided, thereby providing the references of the original research article. Furthermore, it must be ensured in a more reliable way that this knowledge is translated into useful and appropriate advice regarding physical activity during pregnancy. Otherwise, misconceptions are reported such as the often-stated increased compliance of tendons during pregnancy negatively affecting joint stability and the risk of losing balance and falling (Danning, 2013; Nordin and Frankel, 2001; Martin et al., 2015; Blott, 2010; Klausmann, 2002; Engels et al., 2009; McCrory et al., 2010a; Pearson et al., 2011). Scientific evidence from our studies, however, reveal that this claim is false. Patellar tendon stiffness is not affected by pregnancy (Bey et al., 2019a). Therefore, pregnant women do not need to be worried about injuries when exercising due to more compliant tendons.

Second, increased participation in physical activity might be achieved by more obstetricians, gynaecologists and other health care providers encouraging their patients to continue or commence exercising during pregnancy. Many pregnant women do not receive advice regarding physical activity during medical consultations (Evenson et al., 2009).

Third, we believe that appropriate solutions need to be found in order to reduce the fear of injury and falling (Atay and Basalan Iz, 2015). Scientific outcomes may help to convince pregnant women that concerns regarding injuries and falls when exercising are actually not justified. Our findings, for example, have demonstrated that marginal impairments in static postural stability during pregnancy are probably physiologically irrelevant which challenges the assumed necessity of balance enhancing interventions and/or fall prevention strategies in pregnant women.
Additionally, our findings did not point to an increased risk of falling during pregnancy. The commonly-reported increase in the risk of falling during pregnancy is derived from a large cohort study from Dunning et al. (2010) which did not contrast the number of fallers with a reference value from a non-pregnant control group or the same group during another period of time, e.g. after delivery. In contrast, we considered a control group and observed an even larger number of falls occurring in the non-pregnant women (unpublished data, see appendix A.5). This leads to the question of whether the risk of falling during pregnancy has been overestimated in general.

Finally, for increased participation in physical activity it might also be useful to develop strategies to enhance motivation for being active. One strategy might be to emphasize

that pregnancy appears to be a suitable period in a woman's life to be physically active as it provides favorable metabolic conditions promoting muscle adaptation to training and mechanical loading (Falick Michaeli et al., 2015; Rundgren, 1974; Delmonico et al., 2009). Thus, especially in sedentary pregnant women who do not meet the minimum national recommendation of 30 minutes moderate physical activity a day (WHO, 2016) the informative value of this effect may be a crucial key motivator for their participation in a physical activity program.
Furthermore, in the past some efforts were made to develop new ideas for interventions in sedentary adults and children (Dunn et al., 1997). Motivation enhancing interventions may be cognitive strategies involving an increase in knowledge and recognizing the benefits and consequences of not being active (Marcus et al., 1992; Marcus and Simkin, 1993). Behavioral strategies such as reminders to be active, monitoring activity level using accelerometers and apps or rewarding oneself (Lewis et al., 2002; Rousham et al., 2006) may also positively affect attitudes toward physical activity.

In sum, as physical activity is accompanied by several benefits for maternal and fetal health (Montoya Arizabaleta et al., 2010; WHO, 2016; DeMaio and Magann, 2009; Jackson et al., 1995; Clapp, 2003; Owe et al., 2016) we strongly recommend encouraging pregnant women to continue exercising and being active, thereby adhering the WHO and ACOG guidelines regarding intensity and the types of sport (WHO, 2016; ACOG, 2015). However, as misconceptions about physical activity during pregnancy negatively affect attitudes towards physical activity and exercise in pregnant women (Mudd et al., 2009; Dobson et al., 2012; Gaston et al., 2012; Gjestland et al., 2013; Juhl et al., 2012; Zhang and Savitz, 1996), the future objective might be to remove incorrect information, to reduce the fear of falling and injury, and to advise the women about safety and possible risks of physical activity during pregnancy.

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Appendix

A.1: Contribution of the knee flexors' coactivation affecting the knee extensor moment in the early and late stage of pregnancy as well as postpartum

	Contribution of coactivation [%]		
Participant (n = 19)	**Early pregnancy**	**Late pregnancy**	**Postpartum**
PP01	4.0	3.3	1.2
PP02	16.9	24.0	13.0
PP09	9.7	17.1	17.6
PP13	2.8	12.7	2.4
PP14	4.7	6.3	7.0
PP15	5.9	5.6	15.7
PP16	14.2	12.2	16.7
PP20	10.2	6.4	17.8
PP21	8.9	15.7	2.2
PP22	9.8	8.5	5.1
PP23	8.7	10.2	8.5
PP24	7.0	12.1	3.3
PP25	10.1	7.6	6.2
PP26	9.7	9.7	9.2
PP27	4.2	4.4	3.8
PP28	5.5	4.9	3.5
PP29	7.9	5.6	1.3
PP31	19.6	18.7	5.4
PP32	8.5	12.2	8.7
Mean	8.9	10.4	7.4
Standard deviation	4.2	5.4	5.9
p-value*		0.259	

* *one-way repeated measures ANOVA*

A.2: Differences in the knee extensor moment between pregnant fallers and non-fallers in the early and late stage of pregnancy as well as postpartum

		Knee extensor moment [Nm]	
Fallers (n = 6)	**Early pregnancy**	**Late pregnancy**	**Postpartum**
PP01	125.9	128.1	93.5
PP02	213.2	239.3	213.5
PP13	161.2	167.1	141.0
PP23	159.2	158.2	156.8
PP26	151.2	150.5	142.3
PP29	139.3	147.7	125.8
Mean	158.3	165.1	145.5
Standard deviation	27.3	35.2	36.2
Non-fallers (n = 13)			
PP09	188.8	195.5	193.6
PP14	93.6	131.3	131.5
PP15	106.1	86.0	142.3
PP16	134.8	151.7	152.4
PP20	172.5	165.3	180.2
PP21	147.7	141.2	128.4
PP22	94.7	99.5	92.7
PP24	132.0	128.4	120.2
PP25	85.1	78.3	69.2
PP27	139.8	152.9	134.1
PP28	124.8	110.4	132.8
PP31	203.9	183.1	175.0
PP32	162.3	164.5	147.1
Mean	137.4	137.5	138.4
Standard deviation	35.8	34.9	32.6
p-value*	0.246	0.149	0.694

**independent samples t-test between fallers and non-fallers*

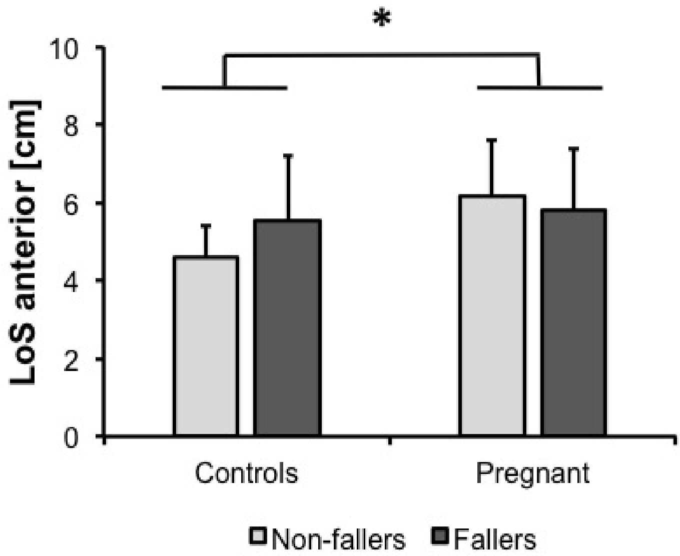
A.3: Differences in patellar tendon stiffness between pregnant fallers and non-fallers in the early and late stage of pregnancy as well as postpartum

	Patellar tendon stiffness [N/mm]		
Fallers (n = 6)	**Early pregnancy**	**Late pregnancy**	**Postpartum**
PP01	1,141	1,219	1,005
PP02	1,192	1,291	1,475
PP13	882	1,077	979
PP23	1,117	1,381	1,192
PP26	1,100	1,054	934
PP29	814	799	637
Mean	1,086	1,204	1,117
Standard deviation	107	124	199
Non-fallers (n = 13)			
PP09	1,498	1,401	1,564
PP14	861	813	1,189
PP15	876	632	1,074
PP16	915	1,064	981
PP20	1,290	1,258	1,240
PP21	1,117	940	909
PP22	1,186	1,195	1,248
PP24	974	903	855
PP25	852	629	828
PP27	859	990	890
PP28	877	736	1,027
PP31	1,224	914	970
PP32	1,358	1,331	1,215
Mean	1,050	972	1,045
Standard deviation	216	240	223
p-value*	0.792	0.221	0.737

**independent samples t-test between fallers and non-fallers*

A.4: Limits of stability in non-pregnant and pregnant non-fallers and fallers

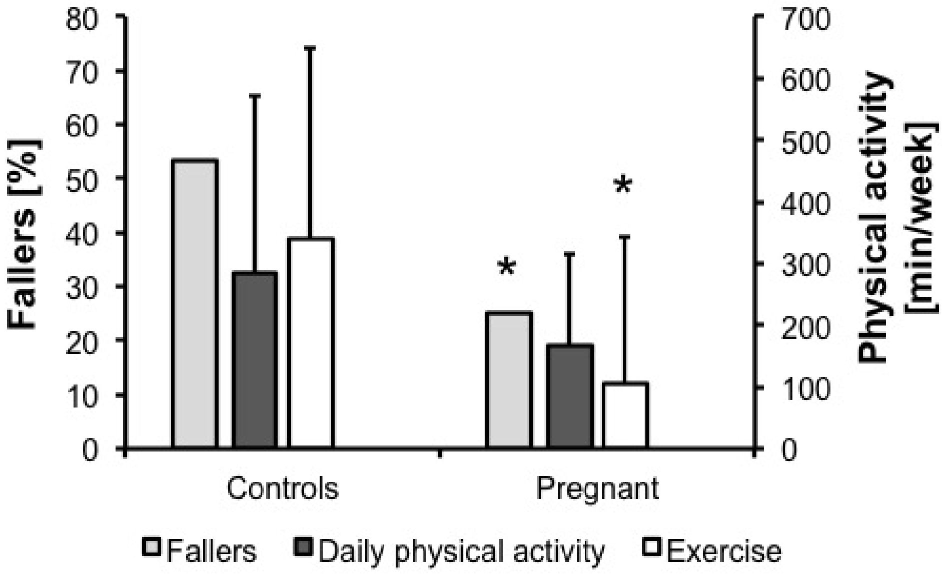
The data were obtained within the framework of our cross-sectional study that included 30 non-pregnant (controls) and 90 pregnant participants (Third research article: The Effect of a Maternity Support Belt on Static Stability and Posture in Pregnant and Non-pregnant Women, chapter 7). Presented are the means and standard deviations.



**significant difference to controls (p-value = 0.544); two-way ANOVA*

A.5: Frequency of falls and amount of physical activity in non-pregnant and pregnant women

The data were obtained within the framework of our cross-sectional study that included 30 non-pregnant (controls) and 90 pregnant participants (Third research article: The Effect of a Maternity Support Belt on Static Stability and Posture in Pregnant and Non-pregnant Women, chapter 7). Presented are the means and standard deviations.



significant difference to controls

Independent samples t-test between controls and pregnant women:

- Difference in the frequency of falls: p-value = 0.018
- Difference in the amount of daily physical activity (daily life situations such as walking or cycling from a to b): p-value = 0.930
- Difference in the amount of exercise: p-value = 0.000

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Statutory declaration

Ich erkläre ausdrücklich, dass es sich bei der von mir eingereichten Arbeit um eine von mir selbstständig und ohne fremde Hilfe verfasste Arbeit handelt. Alle Zitate und sinngemäße wörtliche Wiedergaben, die anderen Werken entnommen wurden, sind unter Angabe der Quelle kenntlich gemacht. Mir ist bewusst, dass Verstöße gegen die Grundsätze der Selbstständigkeit als Täuschung betrachtet und entsprechend geahndet werden. Meine Dissertation wurde nicht anderweitig zum Zwecke der Promotion eingereicht, angenommen oder abgelehnt. Weiterhin erkläre ich, dass ich nicht zwischenzeitlich den Doktorgrad im gewählten Promotionsfach erworben habe.

I hereby declare that the work I have submitted was written independently and without external help. All the sources I used to support my work have been explicitly declared and listed or, where specified, literally quoted. I am aware that violations against the principles of academic independence are considered deception and are punished accordingly. My doctoral thesis has not been submitted elsewhere for the purposes of a doctoral degree procedure. Furthermore, I declare that I have not in the meantime been awarded a doctoral degree in my chosen doctoral subject.

Berlin, den 04. Februar 2020

Marie Elena Bey